Volume 1 MAY 1931 Number 1

Journal of Sedimentary Petrology

A Publication of the Society of Economic Paleontologists and Mineralogists
a Division of
The American Association of Petroleum Geologists

« CONTENTS »

Foreword	*Editor*	1
The Measurement of the Shapes of Rock Particles	*Allen C. Tester*	3
The Petrography of Some Bottom Samples from the North Pacific Ocean	*Stanley A. Tyler*	12
The Heavy Minerals of the Franconia and Mazomanie Sandstones, Wisconsin	*Arthur Pentland*	23
Some Petrological and Paleontological Relations in Subsurface Stratigraphy	*O. M. B. Bulman*	37
Insoluble Residues of the Hunton and Viola Limestones of Kansas	*J. W. Ockerman*	43
Alteration of Comanchean Limestones of South Central Texas	*Marcus A. Hanna*	47
The Clay Minerals and their Identity	*Clarence S. Ross and Paul F. Kerr*	55
Editorial: Sedimentary Petrology in Retrospect and Prospect	*Henry B. Milner*	66

NEW YORK PUBLIC LIBRARY

Journal of Sedimentary Petrology

RAYMOND C. MOORE, EDITOR

ASSOCIATE EDITORS

P. G. H. BOSWORTH
London, England

CLARENCE S. ROSS
Washington, D. C.

MARCUS A. HANNA
Houston, Texas

RALPH D. REED
Los Angeles, California

HENRY B. MILNER
London, England

ARTHUR C. TROWBRIDGE
Iowa City, Iowa

W. H. TWENHOFEL
Madison, Wisconsin

The Journal of Sedimentary Petrology is published semi-annually by the Society of Economic Paleontologists and Mineralogists, a division of The American Association of Petroleum Geologists. Numbers are issued in May and November.

The subscription price of the Journal of Sedimentary Petrology is $3.00 per year prepaid to addresses in the United States, Mexico, Cuba, Porto Rico, Panama Canal Zone, Republic of Panama, Dominican Republic, El Salvador, Bolivia, Colombia, Honduras, Nicaragua, Peru, Hawaiian Islands, Philippine Islands, Guam, Samoan Islands.

Single numbers, $1.75 each.

Postage is charged extra: For Canada, 20 cents on annual subscriptions (total $3.20), and for all other countries in the Postal Union, 40 cents on annual subscriptions (total $3.40).

Claims for non-receipt of preceding numbers of the Journal must be sent to the secretary-treasurer within three months of the date of publication in order to be filled gratis.

The Journal will furnish reprints at cost. Orders should accompany corrected galley proof.

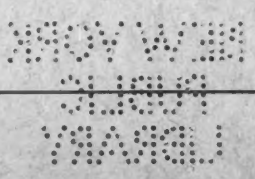
Communications about the Journal, subscriptions, rates, memberships, change of address, and advertising should be addressed to Gayle Scott, Secretary-Treasurer, Texas Christian University, Fort Worth, Texas.

Communications in regard to manuscripts or purely editorial matters should be addressed to Raymond C. Moore, Editor, University of Kansas, Lawrence, Kansas.

Published at Tulsa, Oklahoma

Entered as second-class matter at the Post Office at Fort Worth, Texas, under the act of March 3, 1879. Acceptance for mailing at special rate of postage provided for in section 1103, Act of October 3, 1917, authorized March 9, 1923.

MID-WEST PTG. CO., TULSA, OKLA., U. S. A.



THE NEW YORK
PUBLIC LIBRARY
672031A
ASTOR, LENOX AND
TILDEN FOUNDATIONS
R 1933 L

Volume 1 Number 1

Journal of Sedimentary Petrology

APRIL 1931

FOREWORD

Authorization by the Council of the Society of Economic Paleontologists and Mineralogists of publication separate from the *Journal of Paleontology* of papers dealing with the physical characters and origin of sediments has led, on recommendation of the Editor, to initiation of the JOURNAL OF SEDIMENTARY PETROLOGY. The rapid development in recent years of studies dealing with the processes of sedimentation, the nature and distribution of heavy minerals, insoluble residues, and other constituents of sedimentary rocks, the significance of textures,—in fact, all matters related to the genesis and later history of sedimentary formations,—has outlined a field of geologic science that lacks a medium of expression especially devoted to it. Contributions to knowledge of the subjects that have been enumerated are very widely scattered in geologic literature.

It is not the aim in this venture of the Society to bring together all possible papers that are of interest to students of the sediments. Even if desirable, this would be prohibitively costly and otherwise impractical. There is need, however, to provide suitable means for exchange of information by members and for scientific publication of researches on sedimentary rocks. The Society is interested in minerals as well as in fossils, in sedimentary petrogenesis as well as faunal composition and correlation, in physical as well as organic environment. The association of paleontologist and mineralogist, seemingly unnatural in this day of extreme specialization when neither can thoroughly grasp more than part of one field, is natural in the Society of Economic Paleontologists and Mineralogists, because the study of subsurface geology in oilfield districts requires investigation of both organic and inorganic characters. The paleontologic side of the Society's dual personality has been developed through the *Journal of Paleontology*. Although papers on minerals have appeared in this journal, their inclusion is really anomalous. It is felt that the mineralogic side should have adequate opportunity for independent expression, and it is hoped that this may result in the same sort of advancement that has marked the growth of the paleontologic side.

There remains to be given a word of explanation concerning the title selected for this *Journal*, and a statement of general plans and policy as now apprehended. Petrology is broadly defined as the science of rocks; it is a more comprehensive term than petrogenesis, dealing with the origin of rocks, or petrography, involving essentially the description, especially the microscopic description of rocks. Lithology, which is etymologically equivalent to petrology, has come to be used generally as applying to megascopic characters of rocks. As here understood, therefore, sedimentary petrology is the most inclusive designation possible for all scientific inquiry on the subject of sedimentary rocks. It is regarded as embracing the entire fields of sedimentation or petrogenesis of the sedimentary rocks, sedimentary mineralogy, petrography and lithology. Since the Society is concerned with problems of oilfield discovery and development, it is desirable that contributions accepted for publication in the JOURNAL OF SEDIMENTARY PETROLOGY should have bearing, directly or indirectly, on this *raison d'etre* of the Society. Otherwise, according to present editorial policy, the gates are wide. Contributions of members of the Society are preferred but offerings of nonmembers are not excluded. Plans now call for semi-annual issue of the Journal, but if quantity of accepted papers and financial considerations warrant, the size and frequency of issue may be increased.

THE EDITOR.

THE MEASUREMENT OF THE SHAPES OF ROCK PARTICLES

ALLEN C. TESTER
University of Iowa, Iowa City, Iowa

ABSTRACT

The value of shape analysis of rock particles is discussed. Methods used heretofore are considered unsatisfactory. A new method is proposed which is based on the ratio of the length of the original surface or edge of a rock particle to the portion worn away. The word *curvilinear* is proposed as a new shape term. Technique for measurement is suggested for various size grains.

The study of any stratigraphic sequence has for its purpose, even though it may be used commercially, the increase of knowledge concerning the rocks involved. Such an increase in knowledge will improve the character of the interpretations made concerning these rocks, and therefore, yield a truer picture of their history. To accomplish this end careful field observations must be made, notes taken of minor details and variations of texture, structure, cementation gradations, and bedding relationships. Also, it is now recognized that other features of the rocks are best understood after a complete analytical laboratory study. The degree of precision and completeness of this study may vary considerably to suit the problem. At the beginning of a stratigraphic study when the possibilities are unknown or uncertain, the work should be thorough. One factor or set of analyses may yield results in one study while other factors or sets of analyses may be more valuable in another problem.

Sedimentary rocks have been given so little careful analytical attention that the true value of mechanical, mineral, and shape analyses, contemporaneous structures, alterations and concentrations of minerals is a matter of opinion. When more analyses have been made and compared in conjunction with observations on present day environments, and with more experimental work to check the interpretations, the conclusions can be made and used with greater surety. It is imperative that the data be obtained in a quantitative form to be of comparative value.

The subject of this paper deals with only one of the phases of a complete analysis of a sedimentary rock composed of granular particles.

The shapes and surface features of the constituent grains of a sandstone have often been used as an aid in the recognition of the environment of deposition. More stress has been placed on this criterion than the writer feels is justified. It seems possible that grains of similar shape or surface characteristics are deposited by different agents in environments of a wide range. The question of the relationship of shape and environment of deposition, or shape and amount and kind of transportation, can be settled only after a large amount of quantitative measurements of shape have been made and studied.

A majority of the workers have established a scheme of their own and describe the grains as "rounded," "well-rounded," "sub-round," "sub-angular," "angular," and various modifications of these terms. They have no accurate quantitative basis for classifying the shapes into these groups, and it is very difficult to evaluate or to compare the work of different investigators. Some workers select grains of different shapes, mount them, and use them throughout their particular problem to compare with the grains of the various samples of their studies. This is satisfactory from their point of view, and in most cases the determinations made by them are true to their standards. A good illustration of this method may be had in the work of Trowbridge and Mortimore.[1] Undoubtedly, the grains classified as "round" by Mortimore compare closely with his photograph of round grains. However, another worker who has a different conception of round grains might call such grains "sub-round." The application is of more importance when dealing with grains which have some fresh surfaces and edges but yet have undergone sufficient abrasion to wear the most prominent surfaces and corners. Few attempts have been made to measure the amount of abrasion of sand grains and then express the result in a numerical value so that any stated value would fall in a descriptive division. Arbitrary divisions placed in these numerical values give the basis for the use of such descriptive terms as "round," "sub-angular," or others.

In 1927 Cox[2] discussed this problem and decided that it is possible to make a determination from sand grains which will yield quantitative measurements. He bases his determinations upon the ratio of the area of a cross-section of a grain to the area of a circle which has the same circumference as the perimeter of the measured grain. It is obvious that a grain with a large number of sides and with nearly equal radii

[1]Trowbridge, A. C., and Mortimore, H. E., Econ. Geol., Vol. 20, 1925, pp. 409-423.

[2]Cox, E. P., Jour. Pal., Vol. 1, 1927, pp. 179-183.

when seen in cross-section, will yield a ratio approximating that of a circle with the same perimeter. Even a square, or a cube when considered as a three-dimensional body, will yield a ratio of over 78 per cent, while an isosceles triangle will yield a ratio of 54 per cent. The writer believes that such ratios are misleading, as the cube or pyramid may be fresh and have suffered very little or no wear. He believes that any standard of the measurements of shapes of grains should be based upon the relative amount of abrasion on the grain. This can be called the factor of wear. This means, of course, that some postulate must be made of the original shape of the grain prior to its abrasion. Wentworth[1] bases his considerations and measurements of pebbles and cobbles on a similar principle and expresses it as the roundness or (and) flatness ratio. The writer believes the principle is more appropriate and has a better application to the sand grades than to the cobble or pebbles. A sand grain has fewer developed[2] facets than pebbles. Cox[3] avoids the ratio of wear as a basis of measurement and uses the ratio of areas of the grain at the *time of measurement* as compared with a theoretical area the grain would have if its cross-section were a circle of the same perimeter. This might be called dealing in futures, as it attempts to evaluate the abrasion to be accomplished if a perfect sphere results rather than to judge the shape on abrasion already completed.

The writer is convinced by his observations on the shapes of pebbles and sand grains, gained from field and laboratory studies that the original shape of the rock or grain when it is first subjected to abrasion is a primary control on the ultimate shape. In addition to this, the composition and structure of the fragment sometimes influences the place and rate of abrasion. The nature of the abrading agent is a factor of unknown value and may be a greater influence in the ultimate shape of a pebble in one set of conditions, while in another environment the same agent may have little effect.

It seems proper then that attention be given to the shape of the grain before abrasion in making an evaluation of the amount of wear and classifying the grain as to roundness. Cox[4] does not do this, because to him a cube, or square as seen in outline, has a greater roundness than a triangular form. According to Cox, the rock or mineral particle which

[1]Wentworth, C. K., Jour. Geol., Vol. 27, 1919, pp. 507-521, and U. S. Geol. Surv., Bull. 730-c, 1922, p. 93.

[2]Wentworth, U. S. Geol. Survey, Bull. 730-c, p. 93.

[3]*Op. cit.*, p. 181.

[4]*Op. cit.*, p. 181.

disintegrates from the parent rock as a cube and suffers no transportation or abrasion is already well on its way to roundness, while a particle which happens to break out as an elongate form is penalized by the method of Cox and is placed in a more angular class. In fact it is impossible for a grain to start from the fresh rock, before any abrasion has occurred, with a zero percentage of roundness. Likewise, it is impossible to establish any arbitrary numerical value in the Cox scale which will serve as a basis of reference for non-abraded grains. The shape of the fresh grain causes the percentage of roundness for that particular grain to range between the approximate limits of 20 and 85 per cent. It is highly unsatisfactory to compare a fresh polygonal mineral with a "roundness" ratio of 80 per cent with a rectangular or lozenge shaped grain which has all of its corners and most of its edges worn but with only 70 to 75 per cent of "roundness." There is no method known to the writer which can discount the rounded surfaces sometimes developed on grains by fracturing. The constant, or roundness ration of Cox, is properly determined mathematically, but fails because it does not give a true picture of the abrasional history of the grain. After all, that is the only excuse for desiring quantitative data on the shapes of grains.

The shape of a grain as determined by the ratio of the length of the original edge of a grain to the portion worn away, gives a percentage of wear for that side of the grain. This may include more than one corner of the grain. Stated briefly the result is the ratio of wear to original angularity. For example, in figure 1 the outline of an abraded grain is shown with the simplest projection of the flat edges a, b, c, and d. The projected lines intersect and approximate the sides of a square. The fact that remnant edges aa', bb', cc', and dd' are nearly at right angles indicates that the probable outline of the fresh grain was that of a square, so the projection of the edges is made to conform with that idea. This is the one place in the method where the personal element enters, but in the majority of measurements there is little choice, or the differences in projection make only a small difference in the final percentage figure.

The measurements are made by determining the length of the lines representing the projected edges, as line AB, and the length of the remnant edges, as aa', the total length of AB is the denominator of the fraction and the part of line AB not in contact with the grain (or the difference between AB and aa') is the numerator, or $\frac{AB - aa'}{AB} = \frac{14 \text{ mm.}}{23 \text{ mm.}}$

In the same way $\frac{CB - bb'}{CB}$, $\frac{DC - cc'}{DC}$, and $\frac{DA - dd'}{DA}$, are

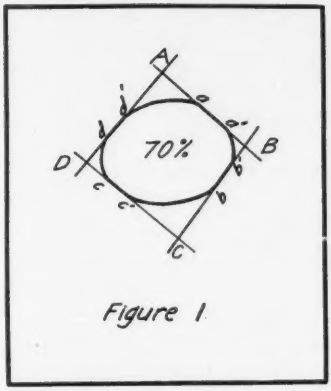


Figure 1. Diagram showing projected edges of rounded grain.

determined. The fractions are worked separately and the average percentage taken, or the numerators and denominators may be totalled and the percentage taken from that fraction.

The complete computations for the determination of the abrasion ratio of the grain of figure 1 follow.

$$\frac{AB - aa'}{AB} = \frac{14}{23} = 61\%$$

$$\frac{CB - bb'}{CB} = \frac{18}{24} = 75\%$$

$$\frac{CD - cc'}{CD} = \frac{19}{24} = 79\%$$

$$\frac{DA - dd'}{DA} = \frac{16}{24} = 67\%$$

$$\text{Totals} \quad \frac{67}{95} = 70.5\% \qquad \frac{4)282}{70.5\%}$$

For the grain in figure 1 the total length of the original outline as projected is 95 mm., and the total length of the remnant sides is 28 mm, so the ratio of remnant edges to original edges is 0.295, and the ratio of abraded edges or that part worn away, to the original edges is 0.705, or

70.5 per cent of total original margin has been worn away. This does not give a measure of the volume of material worn off the grain but numerous measurements of the grain in a variety of positions yields such results. In actual practise an attempt is always made to make three sets of measurements, each set being in the plane of one of the major axes.

The shape of the grain may be expressed in the numerical value of percentage of abrasion, or placed in an arbitrary classification. The writer believes the latter method better and has made a classification of five divisions, each with a range of 20 per cent, as indicated in the table below, with the general names of each division. Experience with this method has shown that even though the percentages have been figured on a large number of grains of a sand, it is better to group these figures under some appropriate term with a definite range.

Percent Abraded	*Class Name*
81 — 100	Rounded
61 — 80	Sub-rounded
41 — 60	Curvilinear
21 — 40	Sub-angular
0 — 20	Angular

It is desirable to use five terms, rather than the usual four, in order to accommodate the large number of grains which have one or more corners or edges well rounded but still retain a prominent part of the original straight edges or angular corners. It is this type of grain which gives so much trouble to the worker who is making his determinations by direct comparison; or, when one worker attempts to correlate his determinations with those of another. The term curvilinear is suggested for the division of 41 to 60 per cent of abrasion, which includes most of the grains mentioned above. The term suggests a polygonal outline with curving lines, not exactly straight nor having easily recognized short curves. It is true also that some of the edges or sides of a curvilinear grain may be straight, but in addition the grain has rounded margins. The class division is more satisfactory than the name.

Reference to figure 2 shows clearly the type of grains included in some of the different divisions. These outlines were taken from Cox[1] and show his roundness ratios as well as the measurements made by Wentworth.[2] The dotted construction lines are shown to illustrate the

[1]*Op. cit.*, p. 181.

[2]Wentworth, Jour. Geol., Vol. 27, 1919, p. 514.

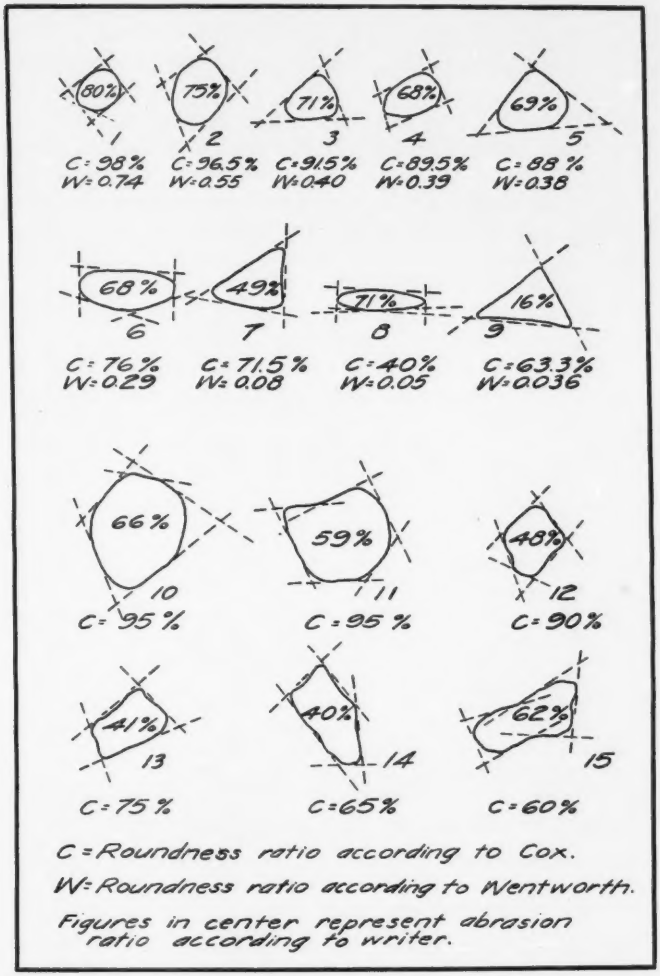


Figure 2. Diagrams showing roundness ratios of rock particles.

manner in which the measurements were made. The percentages shown in the center of each grain are those determined by the writer, while the figures below show the measurements made by Cox and Wentowrth. There is a wide range in the comparative percentages. This is to be expected as the basic principle of measurement is different in each case. In grain No. 1, nearly perfectly round according to Cox, there are definite flat edges on three sides. This immediately raises doubt in the mind of the discriminating analyst. The actual measurement shows the length of these flat sides to be too great to fall in the "rounded" class as designated by the writer. The greatest variation comes, however, in the decidedly angular grains like Nos. 7, 9, and 14, and those grains with a large number of edges but with a perimeter approaching a circle, like grains Nos. 10 and 11.

The simplicity and numerous means of measurement favor the writer's method. He has made measurements in a variety of ways, all of which are satisfactory, but each having its own place or best use. The method used depends largely on the size of the grain; if small, one of the projection types is best; if large the binocular can be used readily; if a cobble or pebble, a hand device is always used. The methods used for particles smaller than peanut pebbles are outlined briefly in the following paragraphs.

A. Indirect Methods.

1. Outline of grain is sketched, enlarged or reduced, and measurements made with a millimeter scale or other convenient unit. (The writer uses a 1–50-inch scale). Only used for rough work.
2. Outline of grain is traced from microscope enlargement by use of camera lucida, or on a ground glass mounted above the ocular of the microscope. (The writer has used the focusing ground glass of the Leitz photomicrograph camera).
   Measurements made from drawing in regular manner.
3. Project the grains on a horizontal screen with a micro-projector, then either trace the outlines, or measure them directly. (The writer has used a small Leitz micro-projector "Urdia"). The direct measurements may be made by using a cyclometer map measurer, determining the total length of the tangent edges and calculating in the regular manner.

To make the measurements of the drawn or projected outlines a convenient scale may be made by using two strips of celluloid or strong paper with millimeter or other convenient scales marked on the edges; the two strips are fastened together so they will swing from a common center. The principle of the fastening is similar to that used in the inexpensive contact goniometers.

B. Direct.

1. Using a petrographic microscope with mechanical stage and ocular micrometer. The grain is moved into position with the mechanical stage so that the edge to be measuree is on the micrometer scale. The straight line serves as the projection of the side being measured and the divisions of the scale give the proportions worn and remaining edges.
2. Using a binocular microscope with an ocular micrometer in each eye piece. When oculars are properly centered and focused the two scales have a common center and by turning one ocular or both, two sides may be projected and the measurements of the abraded and remnant edges made direct.

Any method which will increase the relief of the grain in the field of view aids in making the measurements, especially in determining the units of length of the remnant edges. The use of the lowered condenser or refraction liquids is helpful. When the binoculars are used, a strong light reflected from the mirror slightly tilted is satisfactory if care is taken that the shadow of the grain does not mask the margin.

A hand device called a shapometer for measuring cobbles and pebbles will be described in a later paper. The theory and fundamental principles of this method have been thoroughly tested with this instrument and exceptionally satisfactory results have been obtained.

THE PETROGRAPHY OF SOME BOTTOM SAMPLES FROM THE NORTH PACIFIC OCEAN

STANLEY A. TYLER
North Dakota Agricultural College, Fargo, North Dakota

ABSTRACT

Sixteen samples of mud and one sample of sand, dredged from the bottom of the North Pacific Ocean, at depths ranging from 276 feet to 13,134 feet, are described, and their mineral constituents determined. Complete chemical analyses of eight samples are given.

INTRODUCTION

This paper contains the results of a petrographic study of sixteen samples of mud and one sample of sand taken from the North Pacific Ocean at depths ranging from 276 to 13,134 feet.

The author wishes to express his appreciation for the helpful direction of the research by Dr. W. H. Twenhofel; to the commanding officer of the U. S. Coast Survey Ship, "Surveyor," for the collecting of samples 1 to 13 inclusive; to Dr. T. W. Vaughan for samples 14 to 17 inclusive; and to Dr. V. E. Barnes for valuable help in determining hypersthene by the double variation method of the refractive index.

DATA AND RESULTS

The locations of the samples and the depths from which derived are given in Table 1, and maps (Figs. 1-3) show the relation of the locations of the samples to the coast.

The percentage of clay in the samples was determined by adding ammonium hydroxide to a sample and placing the mixture in an agitating device for twenty-four hours, thus bringing about the deflocculation of the clay. The sand and the clay were then separated by the fractional decantation method. Everything which did not settle within thirty seconds was considered clay and decanted. The material which settled, silt and sand, was treated with tetrabromoethane (sp. gr. 2.9-3.0) and separated into light and heavy minerals, the separation being made in an evaporating dish, as described by Reed.[1] Both portions were then

[1]Reed, R. D. Some methods for Heavy Mineral Investigation. Econ. Geol., Vol. 19, No. 4, 1924, pp. 320-337.

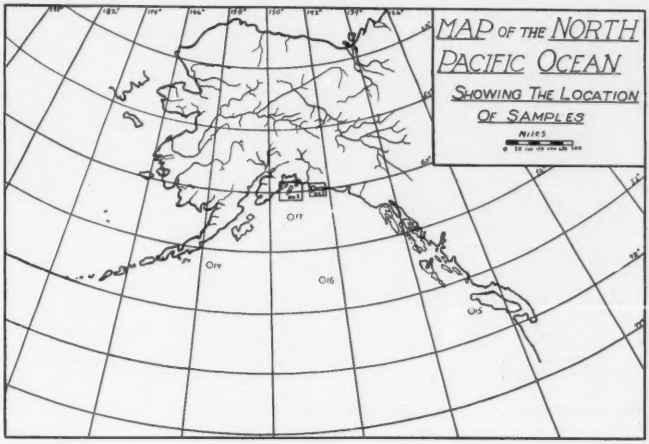


Figure 1

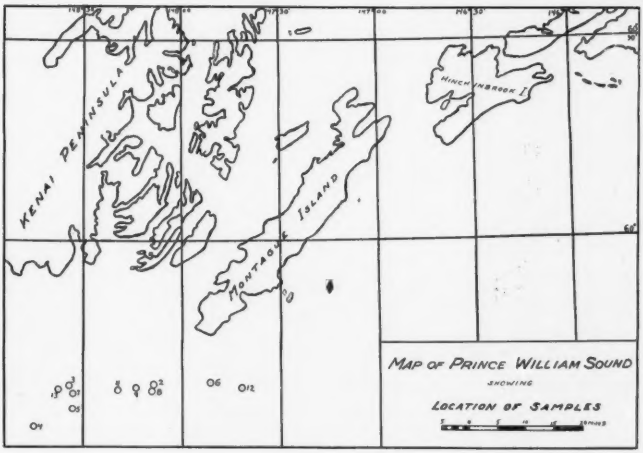


Figure 2

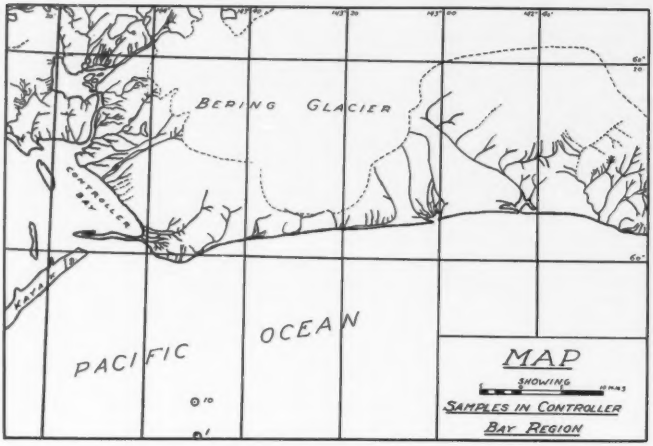


Figure 3

TABLE 1

Location and Depth of Bottom Samples

Sample No.	*Latitude*	*Longitude*	*Depth in Feet*	*Temperature F.*
1	59° 42′ N.	143° 49′ W.	468	43°
2	59° 38′ N.	148° 09′ W.	330	47°
3	59° 38′ N.	148° 33′ W.	390	
4	59° 32′ N.	148° 45′ W.	276	44.8°
5	59° 34′ N.	148° 32′ W.	336	44
6	59° 38.6 N.	147° 51′ W.	408	44°
7	56° 36′ N.	148° 32′ W.	612	
8	59° 37′ N.	148° 10′ W.	528	43°
9	59° 37′ N.	148° 14′ W.	720	42.5°
10	59° 45′ N.	143° 50′ W.	433	
11	59° 57′ N.	148° 20′ W.	642	
12	59° 37.5′ N.	147° 43′ W.	....	42°
13	59° 37′ N.	148° 38′ W.	306	
14	55° 08′ N.	156° 55′ W.	1380	
15	50° 11′ N.	129° 17′ W.	....	
16	53° 49′ N.	144° 05′ W.	13134	
17	58° 20′ N.	147° 39′ W.	4260	

dried and weighed and the percentages of the light and heavy minerals determined.

Chemical analyses of samples 1 to 8 were made in the Chemical Laboratories of the University of Wisconsin by Mr. Willard Woodstock

under the direction of the late Professor Geo. B. Kemmerer. The results of the analyses are given in Table 2.

TABLE 2

Chemical Analyses of Bottom Samples

Sample No.	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*
SiO_2	54.88	55.64	52.23	43.83	50.74	51.89	52.31	42.86
Fe_2O_3	6.78	6.66	9.06	6.79	7.27	8.63	8.05	9.19
Al_2O_3	15.75	14.01	15.98	12.59	14.63	17.15	16.71	23.09
TiO_2	.93	.75	.81	.92	.79	.87	.88	.97
P_2O_3	.21	.18	.20	.19	.17	.19	.18	.18
CaO	4.44	5.91	4.20	13.85	7.88	4.11	4.76	6.41
MgO	4.54	3.76	4.88	3.82	3.36	4.68	4.36	5.20
MnO	.17							
K_2O, Na_2O	6.80	5.92	4.42	4.10	5.54	4.89	4.77	5.15
Loss CO_2, HO_2 Organic.	5.57	7.17	8.22	13.91	9.72	7.59	7.98	6.95

The percentages of clay in the samples range from 45.97 to 97 per cent. The graph, figure 4, shows the percentage of clay as determined by the decantation method, the percentage of kaolin as determined from the chemical analysis, and the material other than kaolin in the clay.

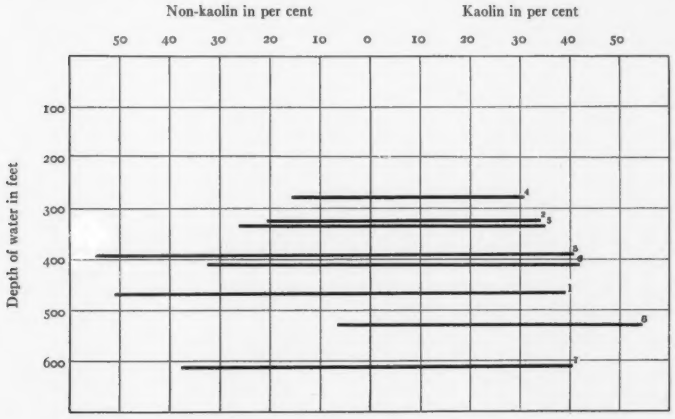


Fig. 4. Diagram showing clay content of bottom samples and depth.

The entire line indicates the percentage of clay in the samples as determined by the decantation method. The percentage of kaolin in the clay was computed from the amount of alumina as shown by the chemical analysis, the quantity of alumina used by the feldspars being taken into account. The remainder of the clay which is not kaolin probably is composed mostly of very finely divided quartz or colloidal silica which decanted because of its fineness.

Table 3 shows the percentage of clay as determined by decantation, the percentage of kaolin as calculated from the chemical analysis, the percentage of the remaining material which composes the clay, and the percentage of light and heavy minerals.

TABLE 3

Percentage of Light and Heavy Minerals and of Clay in Bottom Samples

Sample No.	*Per Cent Light Minerals*	*Per Cent Heavy Minerals*	*Per Cent Clay*	*Per Cent Kaolin*	*Remainder of Clay*
1	9.54	.15	90.31	39.10	51.21
2	44.47	.53	55.00	34.20	20.8
3	4.60	.02	95.37	40.40	54.97
4	52.25	1.12	46.53	30.70	15.83
5	38.40	.29	61.29	35.00	26.2
6	24.74	.02	75.24	42.60	32.64
7	21.61	.13	78.26	40.05	37.76
8	38.46	.49	61.04	54.60	6.44
9	2.96	.03	97.00		
10	3.99	.17	95.87		
11	4.67	.02	95.29		
12	6.91	.11	92.96		
13	53.58	.42	45.97		
14	94.03	5.96	.....		
15	44.47	.52	55.00		
16	11.53	.21	88.26		
17	28.11	.05	71.85		

The percentages of the heavy minerals range from 1.12 to 0.02 per cent, thirteen samples having less than one-half of one per cent. Sample 14, a sand, contains 5.96 per cent of heavy minerals. This is high and is due to the presence of large particles of magnetite.

Light Minerals. Table 4 gives the percentages of light minerals and shell fragments.

The light minerals were mounted both in oils and in Canada balsam, and identifications were made by optical methods. The quantity of each mineral present was determined by counting several hundred grains and representing abundance in percentages. In table 4 the percentage of quartz and feldspar is subject to some error because the smallness of

many of the grains combined with indistinctness of the interference figures made it extremely difficult to differentiate them.

The following minerals and shells were found in the light portion of the samples: mineral aggregates, quartz, feldspar, calcite spherulites,

TABLE 4

Analyses of the Light Minerals in Bottom Samples, by per cent

Sample Number	*Aggregates*	*Quartz*	*Feldspar*	*Calcite Spherulites*	*Foraminifera (other than* Globigerina)	*Radiolarian and diatom tests*	*Shell Fragments*	*Sponge Spicules*	*Isotropic Material*	*Glass*	Globigerina *Tests*
1	46	28	20	22	2	1	1	..	..	..	..
2	45	37	6	10	1	..	..	1	..	..	..
3	62	7	6	9	3	1	..	12	..	..	..
4	30	10	4	12	2	3	30	4	..	..	5
5	17	15	11	20	1	1	25	10	..	..	..
6	68	23	5	2	1	..	..	1	..	..	..
7	58	12	18	5	1	..	2	3	..	..	..
8	45	15	20	6	3	..	11	..	..	..	..
9	51	17	22	3	4	..	3	..	..	..	..
10	21	34	40	4	1	..	..	..	..	..	..
11	59	17	17	2	3	..	..	1	..	..	1
12	25	41	32	1	1	..	..	..	..	..	..
13	44	6	6	16	2	2	21	3	..	..	..
14	50	18	30	..	..	..	2	..	..	..	..
15	44	30	32	..	2	2	..	..	..	..	..
16	40	21	12	3	7	..	..	..	15	2	..
17	66	16	16	..	..	..	..	..	2	..	..

foraminifera (other than *Globigerina*), radiolarian and diatom tests, shell fragments, sponge spicules, isotropic material (probably organic), glass and *Globigerina* tests.

The quartz grains are angular and contain many black and colorless inclusions, which are very irregular in shape and probably are gas or liquid.

The feldspar grains are very angular and also very fresh with the exception of the feldspar in sample No. 14 which is clouded with chloritic alteration products. They contain a few black inclusions and a few colorless prismatic inclusions.

The mineral aggregates are composed of very small particles which in many cases have a slight greenish tinge due to greenish opaque particles. Some of the mineral particles in the aggregates are hornblende.

Extremely small prismatic grains which give parallel extinction are also present. These are probably hypersthene.

Some fairly large clear pieces of glass were found in sample No. 16. Their origin is uncertain.

Pebbles. Samples 2, 3, 4, 5, 8, and 13 contain a few subangular to well rounded pebbles, the largest being about one-eighth inch in diameter. They are coated with manganese. Thin sections made of pebbles from samples 2, 3, 4, and 5 gave results as follows. Sample No. 2—Fairly fine grained gneiss. Constituents—Quartz, orthoclase, plagioclase, and sericite. The sericite has very obvious parallel arrangement. Sample No. 3—Medium to coarse grained gneiss. Constituents—Quartz, orthoclase, plagioclase, and sericite. Sample No. 4—Same as pebble from Sample No. 3. Sample No. 5—Brecciated basalt. Very fine grained quartz matrix.

Heavy Minerals. The heavy minerals were mounted in Canada balsam, identification being made by optical methods. Table 5 gives the percentages of the different heavy minerals present in the samples.

TABLE 5

Analyses of the Heavy Minerals in the Bottom Samples, by per cent

Sample No.	*Hypersthene*	*Hornblende*	*Green Mica*	*Biotite*	*Zircon*	*Garnet*	*Epidote*	*Apatite*	*Staurolite*	*Rutile*	*Cyanite*	*Opaque Minerals*	*Nonopaque Minerals*
1	57	30	..	3	2	2	5	1	..	..	..	20	80
2	74	5	..	4	2	10	5	..	..	..	..	54	46
3	79	10	3	4	1	1	2	..	..	..	..	40	60
4	75	5	4	6	3	2	5	..	..	..	..	40	60
5	73	5	10	3	3	3	2	1	..	..	..	52	48
6	58	31	1	4	..	1	4	1	..	..	..	24	76
7	74	5	1	8	1	3	7	..	..	1	..	55	45
8	69	7	3	1	2	16	2	..	..	..	..	36	64
9	76	14	..	4	1	2	2	1	..	..	..	24	76
10	61	28	..	2	1	4	3	1	..	..	..	33	67
11	59	30	5	2	1	1	1	1	..	..	..	67	33
12	46	31	6	8	2	2	4	1	..	..	..	23	77
13	80	3	6	7	1	1	1	1	2	..	..	45	55
14	70	10	14	1	2	1	2	..	..	..	..	36	64
15	35	40	6	1	6	3	5	2	1	..	1	43	57
16	70	10	..	1	6	3	5	3	1	..	1	52	48
17	42	42	3	1	6	2	4	..	..	..	..	42	58

DESCRIPTION OF MINERALS

Hypersthene. Hypersthene is present as perfect crystals and also as angular to subangular grains. The hypersthene crystals range in size from 0.1 mm. by 0.4 mm. to 0.02 mm. by 0.1 mm. Many of the crystals are coated with a colorless isotropic substance, the identity of which is not known. Black, brown, and colorless inclusions are very abundant in most of the particles and in many cases small hypersthene crystals are included in larger ones. These inclusions seem to have no regular arrangement. The crystals are pleochroic from green to yellow, and in a few cases from green to red or brown. The angular to subangular grains of hypersthene range in size from 0.35 mm. to 0.02 mm. and probably average about 0.04 mm. in diameter. They are weakly pleochroic to colorless. Considerable trouble was encountered in positively identifying the hypersthene by common optical methods and for this reason the optical properties of the crystals were determined by Dr. V. E. Barnes using the double variation method of refractive index as described by R. C. Emmons.[1] The results are as follows.

Refractive index—

γ — 1.7022 ± .0002		$\gamma - \alpha$ .0120
β — 1.6990 ± .0006		$\gamma - \beta$ .0032
α — 1.6902 ± .0010		$\beta - \alpha$ .0088

Dispersion—

γ F—C .0140 ± .0010		Sign —
F—D .0095 ± .0010		2V Cal. 60° 6°
D—C .0045 ± .0010		2V Obs. 66° 4°
α F—C .0133 ± .0020		Z — c 0°
F—D .0093 ± .0020		
D—C .0040 ± .0020		

Hornblende The grains are lath-shaped to angular. Very few rounded grains are present. The lath-shaped grains range in size from 0.12 mm. by 0.4 mm. to 0.05 mm. by 0.1 mm. The angular grains range in size from 0.01 mm. to 0.1 mm. and average about 0.03 mm. in diameter. The grains are very fresh and unaltered. Some grains contain a few black inclusions. The color of the hornblende ranges from dark green and dark bluish-green to a very light green.

Epidote. The grains vary from round to subangular, minimum and maximum diameters being respectively 0.01 mm. to 0.2 mm. and the average diameter 0.03 mm. The color is yellowish-green. Inclusions are very rare and the grains are unaltered.

Garnet. The grains range in size from 0.02 mm. to 0.2 mm., the average size being about 0.05 mm. The large grains are generally subangular to rounded whereas the small grains are angular. Some of the grains have hackly and etched surfaces and a few contain small black inclusions. The colorless garnets are the most abundant, but some pink and purple varieties are present.

[1]Emmons, R. C., Am. Mineralogist, Vol. 13, 505, 1928; Vol. 14, 414, 1929; Vol. 14, 441, 1929.

Zircon. The shapes of the grains vary from rounded to prismatic. The crystals range in size from 0.01 mm. by 0.03 mm. to 0.1 mm. by 0.4 mm., and the rounded grains from 0.02 mm. to 0.2 mm. The grains are colorless and rarely contain a few black inclusions.

Biotite. Biotite is present in the sediments as fresh, brown cleavage flakes which contain a few black inclusions. Most of the grains are lath-shaped with ragged edges, but some are angular. The grains range in size from 0.02 mm. to 0.3 mm.

Green Mica. Green mica occurs in the sediments as fresh, green to greenish-brown, irregular cleavage flakes with a few small black inclusions. The grains range in size from 0.01 mm. to 0.15 mm. by 0.3 mm.

Apatite. Most of the grains are well rounded, but there are a few with crystal outlines. They are fresh, colorless, contain a few black inclusions, and average about 0.04 mm. in diameter. The crystals range from 0.02 mm. by 0.04 mm. to 0.05 by 0.1 mm.

Staurolite. Staurolite occurs as angular grains with hackly surfaces, and is pleochroic from golden gellow to reddish-brown. The grains range in size from 0.03 mm. to 0.3 mm.

Rutile. Rutile is present as dark-brown needle-like crystals with dimensions about 0.02 mm. by 0.2 mm.

Kyanite. Kyanite is present as colorless, lath-shaped grains with good cleavage. Some of the grains are somewhat altered to a yellowish-green mineral, while other grains are fresh. The average size is about 0.08 mm. by 0.2 mm.

Opaque Minerals. The opaque minerals consist principally of magnetite. Some ilmenite probably is present, but it was not positively identified. The average diameter of grains is about 0.05 mm. Maximum diameters are 0.08 mm., and the minimum diameters 0.01 mm. The grains range from well rounded to angular, but the majority are either angular or subangular. Some samples contain clusters of extremely round grains. The diameters of these grains approximate 0.02 mm. They may be composed of manganese.

The following table gives the sizes of the heavy mineral grains measured in millimeters by means of a micrometer ocular. Italicized figures denote average diameters.

SUMMARY

1. The percentages of heavy minerals range from 0.02 to 1.12 per cent in the samples of mud. The heavies constitute 5.96 per cent of sample number 14 which is sand.

2. The chemical analysis and the petrographical examination show that a considerable part of the clay is not kaolin.

3. Mineral aggregates: quartz, feldspar, calcite spherulites, radiolarian and diatom tests, shell fragments, sponge spicules, isotropic material (organic?), glass and foraminiferal tests, are present in the light portions of the sediments.

TABLE 6

Sizes of Heavy Minerals in Bottom Samples, in Millimeters

Sample	*Hypersthene*	*Hornblende*	*Green Mica*	*Biotite*
1	.10—.02 *.04*	.14×.05—.05	.14×.05—.05	.10
2	.40×.10—.12×.05	.40×.12—.05		.30×.15
3	.20—.02	.30×.13—.05	.30×.08—.04	.30×.10—.03
4	.30×.17—.03	.30×.18—.02	10×.04	.13—.03
5	.30×.09—	.20×.08—.03	.20—.10	.20—.02
6	.10—.02	.07—.02	.10—.01	.10—.02
7	.30×.05—.05	.20×.10—.02	.25—.03	.20—.05
8	.40×.10—.02	.30—.02	.20—.01	.25—.02
9	.20—.02 *.05*	.20×.05—.03		.15—.02
10	.08—.02	.10—.02		.08—.03
11	.10×.02—.02	.10×.05—.03	.10	.08
12	.08—.01	.10—.01	.20—.05	.20—.05
13	.30×.10—.05	.20×.09—.02	.18—.03	.20—.05
14	.35—.10	.30×.10—.01	.50×.20—.15	50×.20—.20
15	.20—.03	.20×.08—.05	.15	.10
16	.50×.01—.30×.15	.20—.03		.20—.05
17	.20×.05—.02	.20—.02	.25—.10	.20

Samples	*Zircon*	*Garnet*	*Epidote*	*Apatite*	*Opaque Minerals*
1	.08×.02—.04×.02	.07—.04	.10—.02	.04	.17—.03 *.05*
2	.20×.09—.08	.20—.03	.10		.70—.05 *.20*
3	.03—.01	.10—.02	.05—.02		.30—.01 *.05*
4	.12×.02—.01	.30—.01	.10—.03		.80—.02 *.07*
5	.04×.01	.20—.05	.05—.02	.03	.30—.03 *.05*
6		.08	.03	.03—.01	.05—.03
7	.06×.01	.08—.02	.17—.05		.20—.03 *.07*
8	.15—.10	.20—.02	.20—.02		.30—.02
9	.10×.02	.02	.02	.04×.03—.02	.30—.01
10	.03×.01	.10—.04	.03	.08×.02	.05—.02
11	.10×.025	.02	.02	.03	.40—.01
12	.10×.03	.08	.05	.03	.10—.01
13	.10—.03	.04	.03	.03	.20—.01
14	.10	.10	.07		.25—.10
15	.20×.02—.40×.10	.12	.10—.01	.08—.02	.30—.03
16	.20— 02	.20—.05	.20—.10	.10—.05	.30—.02
17	.10—.05	.20—.10	.05—.02		.30—.02

Samples	*Staurolite*	*Kyanite*	*Rutile*
7			.20×.02
13	.15×.07		
15	.20×.03	.20×.08	
16	.15	.20×.08	

4. The pebbles of the samples are coated with manganese and were derived from gneisses and brecciated basalt.

5. Hypersthene, hornblende, green mica, biotite, zircon, garnet, epidote, apatite, staurolite, rutile, kyanite, magnetite, and opaque minerals, compose the heavy minerals. Hypersthene is the most abundant heavy mineral.

6. The freshness of the minerals together with abundance of feldspar indicates that chemical decay played little part in the production of the particles.

7. The mineral suite seems to be continuous over the area from which the samples were taken.

THE HEAVY MINERALS OF THE FRANCONIA AND MAZOMANIE SANDSTONES, WISCONSIN

ARTHUR PENTLAND
University of Wisconsin, Madison, Wisconsin

ABSTRACT

The light minerals of the Franconia and Mazomanie sandstones are quartz, glauconite, feldspar and dolomite. The chief heavy detritals are garnet, tourmaline, zircon, white mica, limonitized glauconite, opaque minerals and shell fragments. It is concluded that the Mazomanie should be correlated with the upper part of the Franconia.

INTRODUCTION

The microscopic investigation of the Franconia and Mazomanie sandstones was undertaken in order to determine to what extent the heavy minerals of these sandstones show similarities and relationships. It was also hoped that the heavy minerals would give information as to sources of the composing materials of the sandstones and thus possibly portray the paleogeography at the time of deposition.

Samples were collected from outcrops in south-central and southwestern Wisconsin and separated into "heavy" and "light" portions by means of tetrabromoethane (specific gravity 2.9 to 3.0). Both the heavy and the light minerals were examined microscopically, more attention being given the former.

The work was done in the Sedimentation Laboratory at the University of Wisconsin. The author wishes to render grateful acknowledgment to Dr. W. H. Twenhofel for directing the research, to Mr. F. T. Thwaites for helpful suggestions and for the well samples from Prairie du Chien, and to the other members of the faculty of the University of Wisconsin who have aided in the work.

The Franconia and Mazomanie sandstones are of Upper Cambrian age. The Franconia is typically developed in eastern Minnesota and the western part of Wisconsin; the Mazomanie in the south-central part of the latter state. They have been considered as separate formations by some students and the same formations by others. Ulrich[1] states

[1]Ulrich, E. O., Jour. Washington Acad. Sci., Vol. 10, 1920, pp. 73-77.

that the Mazomanie overlaps the Franconia. Relations to preceding and succeeding formation are shown by sections in western Wisconsin and near Madison.

The stratigraphic succession in the vicinity of Madison[1] in-

Stratigraphic section of the Tomah and Sparta Quadrangles, Western Wisconsin[2]

	Thickness in Feet
St. Peter	70
Unconformity	
Oneota	0–170
Disconformity	
Madison	0–16
Disconformity?	
Jordan	26– 40
St. Lawrence	78–110
Disconformity	
Franconia	120–173
Disconformity	
Dresbach	590–615
Disconformity	

cludes, in upward order, (1) Dresbach sandstone, (2) Mazomanie sandstone, (3) Trempealeau (St. Lawrence), (4) Madison sandstone, and (5) Oneota dolomite.

Twenhofel and Thwaites[3] divide the Franconia of the Tomah-Sparta quadrangles into five members as follows:

(5) Upper greensand, thickness 54 to 70 feet
(4) Yellow sandstone, thickness 40 to 50 feet
(3) Lower greensand, thickness varies around 40 feet
(2) Micaceous shale, thickness varies around 15 feet
(1) Basal sandstone and overlying calcareous layer, thickness 1 to 10 feet. The basal sandstone is now differentiated as the Ironton member.

THE MINERALS OF THE FRANCONIA AND MAZOMANIE SANDSTONES

The light minerals found in the Franconia and Mazomanie sandstones are quartz, glauconite, feldspar, and dolomite. The chief heavy minerals and materials are garnet, tourmaline, zircon, white mica, colored mica, limonitized glauconite, opaque minerals and shell fragments. The opaque minerals are mainly iron oxides in the form of hematite and limonite.

[1]Thwaites, F. T. The Paleozoic Rocks found in the Deep Wells of Wisconsin and northern Illinois, Jour. Geol., Vol. 31, 1923, pp. 542-550.

[2]Twenhofel, W. H., and Thwaites, F. T. The Paleozoic Section of the Tomah and Sparta Quadrangles, Wisconsin. Jour. Geol., Vol. 27, 1919, p. 616.

[3]Twenhofel, W. H., and Thwaites, F. T., *op. cit.*, pp. 624-625.

Quartz. Quartz grains are angular to subangular, rarely well rounded. Some show secondary enlargement due to the deposition of silica. Where this is the case, the nucleus can readily be distinguished by means of a "dirty" ring around it. Occasionally a grain shows wavy extinction.

Feldspar. The feldspars are orthoclase, microcline and an alkalic plagioclase. Plagioclase more calcic than andesine has not been observed. The feldspars make up not more than one or two per cent of the light minerals. They are usually subangular to angular. Some grains are turbid due to decomposition, but usually they are quite fresh and show bright interference colors under crossed nicols.

Glauconite. Glauconite, with the exception of quartz, is the most abundant mineral in the Franconia and Mazomanie sandstones. It may occur disseminated throughout the beds, in which case it makes up from one to over 20 percent of the minerals present, or it may be concentrated so as to form as high as 50 percent of the mineral content of thin bands of greensand interbedded with relatively pure quartz sandstone. The glauconite is in the form of subangular to well rounded masses of interwoven laminae. Many of the grains appear to be opaque except at the edges where they are light to dark green. Under reflected light they are green, or, in the case of altered grains, mottled green and yellow or brown, the mottling being due to the partial alteration of the mineral to limonite. The higher specific gravity of the altered grains causes them to sink in the tetrabromoethane and to give trouble in the concentrate through masking the other minerals present. No grains were found that appear to be the casts of organisms.

Dolomite. Dolomite (or calcite) is present in large quantities in certain beds where it forms the cementing material. In the crushed samples the dolomite may be in the form of irregular grains, or as well formed rhombs. Owing to its specific gravity (2.8 to 2.9) it is often found with the heavy minerals, and may mask them to some extent because the samples can not be treated with hydrochloric acid until after the shell fragments have been examined.

Garnet. Garnet is the most common heavy mineral, and is, moreover, present in all the Cambrian formations examined. Most of the garnet grains are colorless or slightly pink; some are distinctly red, but the properties are very similar. A few grains contain colorless, needle-like inclusions. The shapes of the grains range from angular to almost spherical, and the surfaces of almost all appear to be covered with fine lines when viewed under the low power of the microscope. This phenomenon is usually thought to be due to dodecahedral cleavage. Under

the high power some of the grains appear to have a cleavage; in others the surface is covered with half octohedra, which, in many grains, are truncated by cube faces. The edges and corners are very sharp and show no signs of abrasion.

The grains appear to have suffered little or no transportation since the faces have developed. This fact becomes significant when it is remembered that the other grains, such as tourmaline and zircon, are usually well rounded. It may be that the faces have developed since the time of deposition. Mackie[1] and Bramlette[2] suggest etching of the garnet. Bramlette finds that the grains will not split along the so-called cleavage, and that he can produce a similar pattern in freshly broken garnet by treating it with hydrofluoric acid.

Tourmaline. The most abundant tourmaline occurs as prisms with the ends well rounded, or as almost spherical grains. Occasionally, irregularly fractured grains are present. The color ranges from almost colorless through yellow and brown to black, less commonly from green to blue. One or two parti-colored blue and green grains were observed. Pleochroism is intense in the brown varieties. The deep blue colored grains often show a good uniaxial figure. Inclusions, usually in the form of needles, granules, or opaque particles, are common. A few prismatic grains show striations parallel to the principal axis.

Zircon. The common type of grain is a colorless to yellow or brown prism with well rounded ends. Pyramidal terminations may be seen on some grains, but usually the ends are so well rounded that these faces can not be observed. Some grains show distinct zoning.

Mica. Three species of mica are found: a colorless mica, a light green colored mica, and biotite. Mica is most abundant in an argillaceous sand or silt near the base of the Franconia, the micaceous shale of Twenhofel and Thwaites. The colorless and green mica are the most abundant, and have very similar characteristics. Both occur as more or less regular flakes, but the green mica has a slightly smaller optic angle than the colorless. Biotite is in the form of rich brown, irregular flakes. In some grains minute inclusions of zircon can be distinguished. Dark brown or black halos are common.

[1]Mackie, William, The Principles that Regulate the Distribution of Particles of Heavy Minerals in Sedimentary Rocks, as Illustrated by the Sandstones of the North-East of Scotland, Trans. Edinburgh Geol. Soc., Vol. 11, 1923, Part II, p. 156.

[2]Bramlette, M. N. Natural Etching of Detrital Garnet. Am. Mineralogist, Vol. 14, 1929, pp. 336-337.

Iron oxide. Iron oxide occurs in the form of irregularly shaped grains of hematite and limonite. Some iron oxide is found in all samples, and it is often very abundant. Probably much of it is derived from alteration of glauconite.

Shell fragments. Shell fragments are very characteristic of the Franconia and Mazomanie sandstone and occur throughout in all sections examined. In many cases they make up a high percentage of the heavy crop, ranging from zero to over 90 per cent. However, they are not present in the Ironton member of the Franconia or in the Dresbach formation, and only a few particles have been observed in higher formations. They are composed of irregularly shaped tabular grains of calcium phosphate. The color ranges from light yellow to deep brown. Most of the fragments are isotropic, but occasional grains show bands of anistropic material, probably calcium carbonate. The refractive index is about 1.640. Many of the grains do not show organic structure, but some do. These may take the form of small holes suggesting punctae in brachiopod shells, the holes being filled with an opaque substance. Other fragments have numerous elevations of various shapes over their surfaces.

The shell fragments have very irregular and jagged edges. They are probably pieces broken from shells by waves or bottom scavengers and they do not appear to have been moved around much by wave action or bottom currents. Occasionally there is a grain with well rounded edges.

LESS COMMON MINERALS

Besides the described minerals, the following heavy minerals are more rarely present: hornblende, hypersthene, epidote, kyanite, anatase, rutile, barytes, apatite and pyrite. These minerals make up only one or two percent of the heavy crop in all but one set of samples examined. They are dominant in the well samples from Prairie du Chien. The significance of these observations will be discussed in another part.

Hornblende. Hornblende is abundant in the Prairie du Chien samples, and may be present in small amounts in other sections. It is usually in the form of elongated platy cleavage flakes. The grains are green and usually show pleochroism. Most of the grains are fresh and angular, but some are altered to chloritic material.

Hypersthene. The hypersthene occurs in prismatic grains, and displays characteristic pleochroism, pink to green. Like hornblende, it is usually quite fresh, but some grains show considerable alteration. Hypersthene is not abundant in any section.

Epidote. Epidote shows the characteristic greenish-yellow color. It is usually irregular in form and rather angular or "platy." Many grains show an uncentered compass-needle figure.

Kyanite. Kyanite is rare in most samples, but is abundant in the Prairie du Chien section, where it is the dominant mineral in some samples. The grains are clear and colorless and the prevailing type is angular prisms, with irregular terminations. The grains usually lie on the (100) cleavage plane. In many specimens the cleavage parallel to (010) is developed, and occasionally the parting parallel to (001). A "stumpy" form is common.

Anatase. Both yellow and blue anatase occur. The grains are usually tabular with straight edges, and show outgrowths. They may look opaque when viewed under the low power of the microscope, or show only a small patch of color near the center of the grain.

Rutile. Rutile is very rare in the Cambrian sediments examined. It occurs as well-formed prismatic grains. One grain showing geniculated twins was found.

Apatite. Apatite appears to be very rare in the samples examined. A few grains of irregular shape are present in some of the samples. They show good uniaxial interference figures.

Pyrite. Pyrite is very abundant in the samples from Prairie du Chien, where is occurs in cubes, octohedra and pyritohedra. Some masses of minute crystals unite to produce aggregates. This mineral was probably produced in place.

EXPLANATION OF THE TABLES

The tables that follow give the approximate percentage of each of the minerals present in the various series of samples. It should be noted that these tables take into account the relative number of grains, but not the relative size. The grains of tourmaline are smaller, on the average, than the grains of garnet, and those of zircon, smaller than tourmaline. Therefore the tables do not represent the chemical composition.

The percentage of grains was determined by counting, a mechanical stage being used. The slide was moved across the stage in a vertical direction and the grains counted. When the edge of the slide was reached, it was moved in a lateral direction a distance equal to the diameter of the field, and then moved across the stage in a vertical direction again. Two counts were made of each slide. The first included the shell fragments, the second did not. The numbers given in the tables are those obtained from the second count, that is, they do not include the shell fragments.

Shell fragments are not included in the numbers because in many cases they are so abundant that they would mask the detrital minerals. The relative abundance is shown by the letters A (abundant, over 50 per cent), C (common, 30 to 49 per cent), R (rare, 10 to 29 per cent) and T (trace, less than 10 per cent).

Mazomanie from Mazomanie, Wisconsin

Sample Number	Distance in Feet Below Contact with St. Lawrence	Shell Fragments	White Garnet	Red Garnet	Brown Tourmaline	Blue Tourmaline	Green Tourmaline	Zircon	Colorless Mica	Green Mica
71[a]	1	A	92	..	6	..	..	2	..	..
72[a]	4	C	72	..	20	3	..	5	..	..
33	6	C	90	..	7	1	..	2	..	..
38	17	A	86	..	12	..	..	2	..	..
40	20	C	90	2	5	1	..	2	..	..
42	22.5	A	84	..	13	..	..	3	..	..
44	24.5	A	90	1	6	..	3	..	..	..
45	26.5	R	87	1	9	..	..	1	1	1
46	28.5	C	85	..	8	1	..	6	..	..
48	33.5	C	94	1	4	..	..	1	..	..
50	36.5	A	62	..	31	2	5	..	..	..
52	40.5	C	68	..	27	..	4	1	..	..
54	45.5	C	92	..	5	..	..	3	..	..
56	49.5	T	96	..	3	..	1	..	..	..
58	56.5	A	78	..	16	..	1	5	..	..
59	59.5	A	90	..	7	1	..	2	..	..
60	63.5	R	84	..	15	..	1	..	..	..
61	67.5	C	84	..	10	..	3	3	..	..
62	70.5	T	88	3	6	..	..	3	..	..
63	73.5	R	91	..	6	..	..	3	..	..
64	76	C	92	..	8	..	..	..	..	..
65	78	T	92	2	4	..	1	1	..	..
66	80	R	86	..	12	..	..	1	1	..
67	82	T	90	2	2	1	2	3	..	..
68	93	C	84	..	8	1	2	5	..	..
69	96.5	R	80	..	12	..	..	8	..	..
70	100	C	77	..	13	..	1	9	..	..

[a]Sample from Black Earth, Wisconsin.

Mazomanie from Maple Bluff, Wisconsin

Sample Number	Distance in Feet Below Contact with Mendota Dolomite	Shell Fragments	White Garnet	Brown Tourmaline	Blue Tourmaline	Green Tourmaline	Zircon	Colorless Mica	Green Mica	Biotite	Hornblende	Rutile
225	1	A	29	36	..	1	21	6	1	6	..	..
226	5	A	57	22	2	..	14	3	..	1	1	..
227	7	A	56	18	3	..	21	2	..	..	..	..
228[a]	11	A	..	..	..	..	..	..	..	..	..	..
229	14	A	45	20	5	1	4	20	5	..	..	..
230	16	R	34	32	2	1	27	3	..	1	..	..
231	18	A	13	28	..	..	33	26	..	..	..	..
232	22	A	13	30	..	..	30	23	..	3	..	1
234	31	T	83	..	..	..	10	7	..	..	..	..
235	34	C	3	76	4	..	15	..	..	1	..	1
236	37	R	17	65	3	..	15	..	..	..	..	..
237	40	R	78	13	..	..	8	1	..	..	..	..

[a]Mainly shell fragments.

Franconia from Norwalk, Wisconsin

Sample Number	Distance in Feet Below Contact with St. Lawrence	Shell Fragments	White Garnet	Red Garnet	Brown Tourmaline	Blue Tourmaline	Green Tourmaline	Zircon	Colorless Mica	Green Mica	Biotite	Hypersthene	Analase	Kyanite
100	0	C	87	1	9	1	..	1	1	..	..	..	..	..
101	1	R	94	..	4	..	..	2	..	..	..	..	..	..
102	2	R	93	..	5	..	..	2	..	..	..	..	..	..
103	4	A	40	..	3	..	2	..	45	..	..	8	..	2
104	7	A	92	..	2	..	..	4	2	..	..	..	..	..
105	11	A	81	..	8	1	..	10	..	..	..	..	..	..
106	14	C	95	..	3	..	..	2	..	..	..	..	..	..
107	22	R	95	..	2	..	..	1	2	..	..	..	..	..
108	25	A	78	..	14	1	..	2	5	..	..	..	..	..
109	33	C	81	..	2	..	..	1	16	..	..	..	..	..
110	47	A	28	..	50	6	2	8	6	..	..	..	..	..
111	50	A	78	..	18	1	..	3	..	..	..	..	..	..
112	52	A	74	15	9	1	..	1	..	..	..	..	..	..
113	55	A	81	4	13	1	..	1	..	..	..	..	..	..
114	57	A	75	..	14	..	..	7	4	..	..	..	..	..
115	60	A	20	..	61	2	6	10	1	..	..	..	..	..
116[a]	65	T	79	15	4	..	..	2	..	..	..	..	..	..
117	70	T	49	47	1	..	..	3	..	..	..	..	..	..
118	83	A	49	..	27	7	6	7	3	..	..	1	..	..
119	84	C	84	..	13	..	..	2	..	..	..	..	1	..
120	86		92	..	2	..	..	6	..	..	..	..	..	..
121	88	A	48	16	30	..	..	6	..	..	..	..	..	..
122	91	C	63	..	22	..	6	9	..	..	..	..	..	..
123	93	A	55	..	17	2	..	21	2	..	..	..	3	..
124	96	R	87	..	5	..	..	8	..	..	..	..	..	..
125[b]	98	A	80	..	14	2	..	3	1	..	..	..	..	..
126[c]	100	A	..	..	..	..	..	..	..	..	..	..	..	..
127[c]	102	A	..	..	..	..	..	..	..	..	..	..	..	..
128[c]	104	A	..	..	..	..	..	..	..	..	..	..	..	..
129	106	R	64	..	17	..	..	9	8	2	..	..	..	..
130	108	T	89	..	6	..	..	5	..	..	..	..	..	..
131	111	R	20	..	74	..	..	5	..	1	..	..	..	..
132	116	C	81	2	9	1	..	7	..	..	..	..	..	..
133[d]	123	C	1	..	..	..	..	1	76	20	1	..	1	..
134	127	C	..	..	..	..	..	2	73	24	..	..	1	..
135	132	C	..	..	..	..	..	..	62	38	..	..	..	..

[a] Top of yellow sandstone.
[b] Top of lower greensand.
[c] Mainly iron oxide and dolomite.
[d] Top of micaceous shale.

CORRELATION

Examination of the tables will show that there is a marked mineralogical similarity between the major part of the Franconia and the Mazomanie sandstones. The micaceous shale member of the Franconia is the only part not similar to the Mazomanie.

Franconia from Tunnel City, Wisconsin

Sample Number	Shell Fragments	White Garnet	Brown Tourmaline	Blue Tourmaline	Green Tourmaline	Zircon	Colorless Mica	Green Mica	Biotite	Hornblende	Anatase
145[a]	A	50	31	5	4	6	4	..	..	..	..
146[a]	R	79	12	..	..	9	..	..	..	..	..
147[a]	C	82	12	..	..	5	1	..	..	..	..
148[a]	A	80	19	1	..	..	..	..	..	..	..
149[a]	A	64	32	1	1	2	..	..	..	..	..
150[a]	A	44	41	3	..	8	4	..	..	..	..
151[b]	C	62	26	..	2	10	..	..	..	..	..
154[c]	..	26	54	..	..	20	..	..	..	..	..
156[c]	T	..	20	..	..	8	72	..	..	..	..
158	R	10	22	1	..	13	44	..	5	2	3
159	A	41	20	..	9	12	15	..	..	1	2
160	A	21	22	..	3	2	50	1	1	..	..
160[a]	A	1	1	..	..	..	55	..	43	..	..
161	R	..	..	..	1	1	59	..	38	..	1
162	C	3	2	..	..	..	77	6	11	1	..
164	T	..	..	..	..	..	61	39	..	..	..
165	R	1	..	..	..	..	92	7	..	..	..
166	R	..	..	..	..	..	90	10	..	..	..
167	T	..	..	..	..	..	85	15	..	..	..
144[d]	A	..	..	..	..	..	..	..	..	..	..
132[e]	..	74	14	..	..	12	..	..	..	..	..
142[e]	..	18	17	1	..	64	..	..	..	..	..
141[e]	..	7	33	..	..	60	..	..	..	..	..

[a]Upper greensand. [b]Yellow sandstone, 24 feet below No. 150.
[c]Lower greensand, mainly iron oxide and glauconite
[d]Contact with Ironton, mainly iron oxide and glauconite.
[e]Ironton.
Samples 141-44, 154-167 from road cut on south side of tunnel.

Both sandstones carry a high percentage of garnet, the average being over 80 per cent of the heavy minerals. Tourmaline and zircon are present in most samples. The average percentage of tourmaline is about 15 or 16; that of zircon, 3 or 4.

An outstanding feature of both sandstones is an abundance of shell fragments. These commonly amount to over 50 per cent of the heavy residue. This fact is important since shell fragments are absent or occur only in very small quantities in all samples from other Cambrian sandstones that have been studied.

Glauconite is most abundant in the Franconia sandstone near the top (upper greensand), and in the beds above the micaceous shale (lower greensand). It is most abundant near the top of the Mazomanie.

There is little definite information relating to the heavy mineral content of other Cambrian formations of the upper Mississippi Valley, the Madison-Jordan unit studied by Ockerman[1] excepted. The author has collected and examined several samples from the Dresbach and Trempealeau formations from different parts of Wisconsin.

The Dresbach appears to be high in zircon; this mineral in some instances composing 60 per cent or more of the heavy detritals. Tourmaline seems to be more abundant than in the Franconia and Mazomanie. Garnet is present in small quantities or is absent. Glauconite seems wanting and shell fragments are very rare. Ockerman found the Dresbach from La Crosse to contain 60 per cent zircon, 25 per cent garnet, and 15 per cent tourmaline.

Franconia from La Crosse, Wisconsin

Sample Number	*Shell Fragments*	*White Garnet*	*Red Garnet*	*Brown Tourmaline*	*Blue Tourmaline*	*Green Tourmaline*	*Zircon*	*Colorless Mica*	*Green Mica*	*Hornblende*	*Kyanite*
31[a]	..	91	..	1	..	..	8	..	..	..	..
30[a]	R	75	..	11	..	..	14	..	..	..	..
28[a]	C	..	..	1	..	..	..	65	34	..	..
27[a]	A	7	..	9	..	..	9	75	..	..	..
26[a]	A	10	..	42	3	..	3	42	..	..	..
25[a]	C	72	..	19	..	..	7	2	..	..	..
24[a]	A	60	..	32	1	4	3	..	..	..	..
23[a]	A	32	..	36	..	8	13	7	3	..	1
22	..	..	..	..	..	..	..	68	32	..	..
21	T	..	..	..	..	..	2	63	35	..	..
20	T	..	..	..	..	..	2	41	57	..	..
19	R	..	..	..	..	..	..	53	47	..	..
18	R	..	..	..	..	..	..	47	53	..	..
12[b]	A	..	..	..	..	..	..	..	..	..	..
11[b]	A	..	..	..	..	..	..	..	..	..	..
10[b]	A	59	..	18	..	..	22	1	..	..	..
9[b]	A	..	..	..	..	..	..	..	..	..	..
8[b]	R	39	5	8	..	..	45	3	..	..	..
7[c]	..	38	..	29	..	3	29	..	..	1	..
6[b]	..	..	..	..	..	..	..	..	..	..	..
32[d]	..	24	..	20	..	..	56	..	..	..	..
1[e]	..	40	..	30	1	3	2	23	1	..	..
2[e]	..	51	1	32	3	5	3	5	..	..	..

[a]Upper part of Franconia.
[b]Mainly iron oxide.
[c]Top of Ironton.
[d]Typical Ironton.
[e]St. Lawrence from Castle Rock.

[1]Ockerman, John, Jour. Geol., Vol. 38, 1930, pp. 343-353.

Lower Franconia from Gotham, Wisconsin

Sample Number	Distance in Feet Above Contact with Ironton	Shell Fragments	White Garnet	Brown Tourmaline	Blue Tourmaline	Green Tourmaline	Zircon	Colorless Mica	Green Mica	Biotite	Hornblende	Anatase
210		A	81	10	1	..	6	2	..	..	..	..
209		A	14	25	3	1	5	51	..	..	..	1
208		C	72	17	..	..	10	1	..	..	..	..
207		C	42	26	..	..	6	25	..	..	..	1
206		A	22	29	..	..	24	24	..	..	..	1
205		T	..	..	..	..	..	66	34	..	..	..
203		A	..	16	..	..	20	62	..	..	..	2
202		A	45	8	..	..	6	40	..	..	1	..
201		R	63	22	1	..	12	2	..	..	..	..
200[a]		A	..	..	..	..	..	..	..	..	..	..
199		C	61	35	1	..	3	..	..	..	..	..
198		A	38	20	..	..	1	40	1	..	..	..
197[b]		A	..	..	..	..	..	..	..	..	..	..
196		A	76	16	..	..	3	5	..	..	..	..
188	19	C	78	12	3	..	6	1	..	..	..	..
189	18	A	23	23	..	..	21	..	..	22	..	11
190	15	A	26	5	..	..	11	49	8	..	..	1
191	12	C	39	3	..	..	3	45	10	..	..	..
192	8	C	9	1	..	..	2	72	14	..	1	1
193	3	R	..	..	..	..	..	80	20	..	..	..
194[c]		..	32	23	..	..	43	2	..	..	..	..
195		..	2	55	2	1	40	..	..	..	..	..

[a]Mainly shell fragments.
[b]Mainly shell fragments.
[c]Top of Ironton.

Well Samples from Prairie du Chien, Wisconsin

Sample Number	Shell Fragments	White Garnet	Red Garnet	Brown Tourmaline	Blue Tourmaline	Green Tourmaline	Zircon	Biotite	Hornblende	Kyanite	Epidote	Apatite	Hypersthene	Barite	Pyrite
75427	..	54	2	2	..	..	4	..	14	8	16	..	..	..	A
75428	T	73	..	1	..	..	1	2	8	2	11	..	2	..	A
75429	R	46	1	12	1	..	5	4	13	..	18	..	..	..	A
75430	T	70	..	17	..	..	10	..	2	..	1	..	..	..	A
75431	R	73	..	23	..	..	..	1	..	..	2	1	..	..	C
75432	R	90	..	..	..	..	6	..	4	..	..	..	..	..	C
75433	R	58	..	12	..	..	..	..	14	8	2	2	4	..	C
75434	R	51	..	11	..	..	8	1	1	28	..	..	..	..	A
75435	T	20	..	5	..	..	2	..	..	73	..	..	..	..	A
75436	T	20	..	5	..	..	2	..	..	72	..	..	1	..	A
75438	R	20	1	4	..	..	13	1	3	58	..	..	..	T	A
75439[a]	R	32	..	13	..	..	49	..	..	3	..	..	3	T	A
75440		21	4	6	..	..	65	..	..	4	..	..	..	T	

[a]Contact with Ironton.

The Ironton, at the base of the Franconia, is a sandstone somewhat similar to the Dresbach in some exposures. It is rarely well sorted. It may contain a high percentage of iron oxide giving it a yellowish or reddish brown color. Mineralogically it is very similar to the Dresbach after the iron oxide has been removed and it may represent reworked Dresbach with the addition of some material.

There is a marked difference between the Trempealeau and the Franconia at Norwalk, Wisconsin. The heavy minerals in the St. Lawrence for 25 feet above the contact consist almost entirely of colorless mica and the bottom beds contain considerable glauconite. This probably represents reworked Franconia. Samples collected at Castle Rock, near Sparta, Wisconsin, from the highest part of the Trempealeau contain colorless mica, with garnet and tourmaline the dominant minerals. Shell fragments and glauconite are not present. Ockerman states that the average analysis of the heavy minerals of the Trempealeau at Cross Plains is 76 per cent zircon, 22 per cent tourmaline, 2 per cent epidote, with anatase and garnet present in small quantities.

Ockerman's study of the Madison and Jordan sandstones led to the generalization that an average analysis of heavy minerals from the Madison, Cross Plains, and Middleton sections is 90 per cent garnet, 8 per cent zircon, and 1 per cent tourmaline. An average analysis from the Sparta section shows 75 per cent garnet, 15 per cent zircon, and 9 per cent tourmaline. An average analysis from the La Crosse section gives 75 to 85 per cent garnet, 11 to 15 per cent zircon, and 9 per cent tourmaline. His tables show that pink garnets are present in almost every sample. They make up 10 per cent of the heavy residues in many samples, and may be as high as 23 per cent.

The data given above show that the Franconia and Mzaomanie are very similar mineralogically, and that they are different from the formations lying above and below. This is by no means conclusive evidence, but it suggests that the two sandstones are a part of the same formation and obtained their composing materials from the same terranes.

PALEOGEOGRAPHY

The dominant detrital minerals in the Franconia and Mazomanie sandstones are garnet, tourmaline, zircon and mica. This suite of minerals implies derivation from pre-existing sediments.

SAMPLES FROM PRAIRIE DU CHIEN

Up to this point little has been said about samples collected near Prairie du Chien. These were taken from a well drilled on the Ahrens

Bros. farm (SE. ¼, SW. ¼ Sec. 18, T. 7 N., R. 6 W.[1]). Casual examination suggests great differences from samples taken from other localities in Wisconsin. Minerals such as kyanite, hornblende, epidote and pyrite make up a large portion of the detrital grains. Well rounded tourmaline and zircon grains are abundant and garnets with characteristic appearance are present. These minerals do not appear in the usual proportions because of the presence of other minerals.

It is possible that some of the minerals present are due to contamination but it is difficult to see how this would account for the uniformly high percentage in all samples tested. It is possible that the samples are contaminated but the only materials that might have done so are glacial deposits. The area is unglaciated, but the well is in the bottom of a valley through which water from the glaciated areas flowed. The water-borne glacial deposits may be responsible in part, but hornblende, anatase and kyanite are present in small quantities in many other samples collected from natural outcrops in the vicinity where there is no possibility of such contamination. Therefore, it seems probable that the minerals actually occur in the Franconia sandstone at this locality.

Hornblende, and especially hypersthene, are not highly stable minerals and their presence in a sediment probably indicates rapid deposition from neighboring sources under conditions that favored mechanical disintegration rather than chemical decomposition of the source rock. The freshness and angularity of these minerals further emphasize the evidence that such conditions existed during the time of deposition.

The source rock may be a local, buried pre-Cambrian ridge of igneous and metamorphic rocks, or it may be farther away. Buried ridges are known in several localities in Wisconsin but well records have failed to indicate the presence of one in the neighborhood of Prairie du Chien.

If the source rock is not in the immediate neighborhood, we may postulate a river flowing over an area of igneous and metamorphic rocks, and carrying the products of weathering to the Franconia sea. The complete solution of the probem will involve a detailed study of the accessory minerals occurring in the igneous and metamorphic rocks that make up the possible distributive provinces.

SUMMARY

The chief points of interest revealed by the study of the Franconia and Mazomanie sandstones are the following:

[1]Iowa Geological Survey, 1927, Deep Wells, Annual Report, pp. 255-256.

1. The heavy residuals contain an abundance of garnet, tourmaline, iron oxide, dolomite and zircon (and mica in the micaceous shale), and a less common occurrence of kyanite, hornblende, hypersthene, epidote, anatase, rutile, etc.

2. Light residual minerals are mostly quartz and glauconite, and less commonly feldspar.

3. The samples from Prairie du Chien are relatively high in kyanite, hornblende, epidote, etc. Kyanite is a flood mineral in some samples. The samples also contain minerals that are characteristic of the normal aspect of the Franconia.

4. There is little variation throughout the area (with the exception of the well samples from Prairie du Chien) in the Franconia (above the micaceous shale) and in the Mazomanie.

5. The minerals in the lowest Franconia are somewhat different from those in the remainder of the Franconia, and from those in the Mazomanie.

6. The mineral assemblage in the Franconia and Mazomanie is different from the assemblages in the formations above and below.

7. Shell fragments (calcium phosphate) are abundant in the Franconia and Mazomanie formations. They are rare or absent in the formations above and below.

8. The study of the minerals indicates that the Mazomanie should be correlated with that portion of the Franconia which lies above the micaceous shale.

9. The greater parts of the sediments were derived from the reworking of older sediments.

10. The sandstone at Prairie du Chien seems to be derived, in part, from the weathering of igneous and metamorphic rocks. The presence of fresh angular minerals such as hornblende and hypersthene indicates that transportation has not been great, and that the conditions of rock destruction were mechanical rather than chemical.

SOME PETROLOGICAL AND PALEONTOLOGICAL RELATIONS IN SUBSURFACE STRATIGRAPHY

O. M. B. BULMAN
Imperial College of Science and Technology, London, England

A great deal of the work which is now being done under the direction of the various Fisheries Boards and Marine Biological Associations on the relations of marine organisms to their habitat has a definite bearing on problems which confront the geologist. The more we know of the conditions controlling the occurrence and distribution of marine faunas of the present, the more it becomes apparent that such faunas are in very delicately balanced equilibrium and that, from the geological point of view, an intimate connection must exist between lithological and paleontological variations. The broad outlines of "Facieskunde"—the discrimination of calcareous and shelly facies and the like—have long been appreciated, but much remains to be done in detail, and this detail will doubtless have its bearing on subsurface correlation work. With a more definitely geological outlook, a special research station, the "Senckenberg," has lately been established in Germany through the energies of Professor Richter for the furtherance of what he terms "Aktuopaläontologie" and "Aktuogeologie"—a study of the paleontological and geological processes and conditions of the present day.

The more or less obvious lithological and paleontological changes which accompany diastrophism are being considered in the slow task of adjustment, and correlation over wide areas, of the larger stratigraphical divisions. As this proceeds, it appears that in many instances faunal variations or differences that have in the past been attributed to contemporaneous facies are in reality a result of local lateral transgressions and the interfingering of sediments that are not strictly of the same age. But the facies conception remains one of very real importance. Indeed, the study of present-day conditions seems to show that we have always to deal with complex, small-scale, lateral variations in environmental conditions which are intimately related to the occurrence and distribution of animal communities.

Petersen advanced the opinion that "as a rule it is best to regard the animals living on the sea-bottom as communities, just as botanists

group together the vegetation of the land into plant communities," and the conception of animal communities is gaining in importance in biological work. These communities are associations of organisms, generally occurring in quite restricted and fairly well-defined areas, and depending on a complex series of conditions involving the relations of one community to another, of members of any community to others of the same community, and again of environment. Nine such communities were recognized by Petersen in Danish waters, and Ford finds that, although recognisable off Plymouth, the species composition is there not always the same. A community may break up into smaller groups, due to non-typical conditions. Environmental factors include the nature of the bottom, depth of the water, temperature, salinity, chemical and bacterial precipitation of salts, pH values, etc.

To the stratigraphical geologist, this introduces fresh difficulties in exact correlation, particularly in subsurface work where it is harder to form an adequate impression of areal distribution, but it may at the same time furnish the explanation of some of the many anomalies. As remarked by Elles, "....a certain amount of *Lateral Variation* or lack of uniformity is only to be expected amongst those (faunas) of the same age when seen in different localities. ....*Vertical Variation* has long been recognised and understood in principle by geologists, but I do not think the same can be said of *Lateral Variation*."

In the actual study of such assemblages, a noteworthy beginning has been made recently by Abrard with the definition of a number of communities in the Lower Tertiary of the Paris Basin, and Abrard makes the important point that, in paleontology, these "associations paléontologiques" will not correspond precisely with animal communities of the present day, owing to the inclusion in them of drifted shells. This "association paléontologique" of Abrard is practically synonymous with the "faunule" of C. L. and M. A. Fenton.

The discussion of such biological problems in a journal devoted to petrology is to this extent justified, that the distribution and occurrence of the communities which may give difficulty to the paleontologist are set against a background which is largely lithological. Some of the environmental factors were enumerated above; we may ask, to what extent can the past operation of such factors be appreciated by the sedimentary petrologist? Recent work in sedimentation, on grade determination, percentage of colloids, presence and origin of organic matter or of minerals (such as phosphates) derived indirectly from it, encourages the hope that valuable information on past conditions may be forthcoming.

Apart from such difficulties in correlation which confront every stratigraphical geologist, there are others peculiar to work in oilfield development which would often make desirable any confirmatory evidence from other branches of geology.

Since a paleontologist's conclusions are usually sound in proportion to the magnitude of the available fauna, it is clear that the smaller organisms (which occur in greatest number and tend to suffer least damage in drilling processes) are the most satisfactory. The foraminifera are so abundant and in other ways fulfil so well the required conditions that it was natural for the paleontologist in search of suitable material for zonal purposes to turn to an intensive study of this group. Many criticisms have been levelled at the use of foraminifera for correlative purposes, especially when the number of genera and species recognized multiplied at an alarming rate. While, however, many do not welcome the process of "species-splitting," it is a logical outcome of an application of the accepted principles of stratigraphical paleontology, either by the economic or the pure scientist. Oilfield work is but a special case of general zoning—fine stratigraphical subdivision is, in fact, both a scientific aim and an economic necessity. We cannot illustrate this better than by comparing two recent opinions. For the oilfield paleontologist, it is stated that "the time value of forams. . . . is entirely dependent on this splitting (of species), for putting together species which are of short range into one long one would entirely defeat the purpose of close correlation" (Cushman), and, expressing the point of view of the pure scientist, Ulrich is no less emphatic that "experience is showing more and more clearly that if we are to get the utmost benefit from the fossils as stratigraphic indices, it is absolutely essential to discriminate species as closely as possible." Nevertheless, there is a view, which has many distinguished adherents, that evolution is more continuous than discontinuous and that with careful zonal collecting the boundaries between species become less and less apparent—that "the distinct characters are seen to be but a passing glimpse of one point in a stream of definite change" (Swinnerton). Elles believes that the evolutionary stage of an organism may be of greater significance than specific determination.

The process of multiplying species, however it may be accepted in principle, still admits two criticisms.

First, an objection occasionally raised (and this applies to all fine-scale paleontological work) is that the higher the degree to which "species-splitting" is carried, the more does the personality of the investigator influence the process of identification. Petrology and mineralogy,

being more exact sciences, are almost immune from this. In practice, however, if one systematist can gain reliable results the main object is secured even though his species are differently interpreted by another.

Second, it is permissible to inquire into the relative merits of the species employed. To define what is meant by a "species" is almost impossible, but we must recognise that species amongst the protozoa (and hence the foraminifera) are in all probability of a different value from those of more highly organised animals. On the authority of Cushman, we may assume that there is "no fusing of different species or genera to form tests of an intermediate character as has sometimes been advanced in theory." Nevertheless, even in the absence of hybrids, foraminiferal species may be of a somewhat plastic nature; no better instance could be cited that Dreyer's study of the variation of *Peneroplis pertusus* from the Red Sea. Many protozoa retain a capacity for physiological differentiation and are prone to the formation of "physiological races" which, though apparently identical, differ in their physiological reactions and effects; and it is known that such "physiological races" are particularly susceptible to environmental changes. If such races occur among the foraminifera (I am not aware that they have been studied in any detail from this aspect) and bearing in mind that the secretion of a test or shell is fundamentally a physiological function, it suggests that the form of the test may exhibit considerable and quite local modifications induced by environment. This is, in other words, a possible explanation of the wide diversity of form exhibited by the smaller foraminifera; but there follows the possibility that, in the foraminifera more than in any other group, the "species" will vary greatly in correlative value and that some will be of a very restricted distribution and can be employed only with due regard to ecology. That characteristic assemblages of the smaller foraminifera have been recognised for many of the Tertiary horizons is evidence that there are species wide-spread in occurrence and reliable for correlation, but I venture to offer the above remarks because, in spite of what has already been accomplished, the work is still at an early stage in its development, when general criticism may reasonably be offered and will probably be welcomed.

It is clear that the study of by far the majority of fossiliferous sediments will be concerned with conditions where sedimentary petrology and paleontology are largely reciprocal but they may in addition have more complementary relations. For the finer subdivisions of the stratigraphic column we have in the past relied almost exclusively upon

paleontology—upon a system of zones drawn as finely as prevailing knowledge will allow by reference to characteristic faunal assemblages. But the necessities of oilfield practice have emphasized the fact, perhaps too frequently overlooked, that mineralogical or petrological characters may in certain cases serve equally well for the determination of minor subdivisions. The most serious limitation of mineralogical or petrological work in this connection is its inability to date the horizons recognised. Heavy-mineral assemblages offer the possibility of a valuable substitute for fossils in barren sediments and they may also furnish an independent check on paleontological conclusions in cases of doubt, provided that the dispersal of mineral grains has been sufficiently rapid. This is because these assemblages are to a large extent independent of those other lithological characters which, as we have seen, are related to the distribution of animal life. To cite a hypothetical case, it is possible that the head-waters of a river may at a certain stage cut back into a previously unexposed igneous complex and so gain access to a distinctive suite of accessory minerals without sufficiently altering the bulk composition of the sediments carried as to influence marine life in the area of deposition. The incoming of a new mineral suite may be of equal value to the incoming of a new fauna, and if it occurred within the limits of a paleontological zone of considerable thickness and uniformity, it would provide the basis of a closer subdivision. At all times it should be remembered as the possible source of an independent datum line. Recently, Edson has claimed that without doubt "heavy minerals serve as a very accurate and practical means of correlating a given sand in a restricted area."

The occurrence of faunal variation unaccompanied by any environmental change is a more controversial subject. Certainly the evolution of planktonic forms is likely to be largely unconnected with the lithology of the sediments into which their remains sink to rest. But further, while some of the lineages which are attributed to "trend-evolution," or orthogenesis, may have arisen in response to environmental stimulus, others, even among bottom-living forms, seem to be strangely unrelated. In the present state of our knowledge, the evolution of the micrasters of the English chalk suggests the occurrence of faunal changes under uniform lithological (and hence ? environmental) conditions.

Such independence, however, is surely of lesser importance than the more prevalent relationships, and it is an unfortunate aspect of specialisation that it should be necessary to plead for a wider outlook among paleontologists and petrologists and for a closer coöperation,

between them. The data of the sedimentary petrologist—detailed descriptions of the heavy mineral assemblages, the general character of the bulk of the rock, and the possible source and mode of origin of the sediments—are constantly published without reference to their paleontological significance. On the other side, much of the finer zoning of today is being undertaken without proper consideration of such environmental conditions as the trained petrologist could often aid in determining. The result is in both cases an accumulation of more or less unrelated facts which will sooner or later need revision somewhat on the lines indicated. Particularly in the study of oil-shales and limestones is the purely petrographical or purely paleontological description in itself incomplete. With such a volume of work as is now being produced, it is worth while to consider how much of value in true stratigraphical geology is being missed through the lack of such coöperation.

INSOLUBLE RESIDUES OF THE HUNTON AND VIOLA LIMESTONES OF KANSAS

J. W. OCKERMAN
Kansas Geological Survey, Lawrence, Kansas

The Forest City Basin[1] and the Salina Basin in Kansas contain the following pre-Mississippian stratigraphic divisions: Pre-Cambrian granite, Arbuckle limestone, Simpson formation, Viola or Urschel[2] limestone, Sylvan or Maquoketa shale, and Hunton or Younkin limestone. In the identification and correlation of these formations in wells in these basins it is often difficult to differentiate between the Hunton and Viola limestones, especially when the Sylvan shale is not well represented. The use of the insoluble residues of limestones as described by McQueen[3] has been applied to the problem of the identification of the Hunton and Viola limestones with useful results.

The Empire Oil and Gas Company's Schwalm No. 1 in sec. 19, T. 12 S., R. 11 E., Wabaunsee County, Kansas, topped the Mississippi lime at 2,485 feet, Kinderhook shale at 2,705 feet, Hunton limestone at 2,995 feet, Sylvan shale at 3,215 feet, Viola limestone at 3,280 feet, and Simpson at 3,399 feet, the bottom of the well at 3,431 feet apparently still in the Simpson. It is generally agreed that the beds designated above as the Hunton, Sylvan, and Viola, occupy the same stratigraphic position as the Hunton, Sylvan, and Viola of Oklahoma but whether they are the exact equivalents of the Oklahoma beds is not certain. Barwick,[4] Edson,[5] and McClellan[6] have discussed the problem of the names and correlations of the pre-Mississippian beds in its various aspects. The

[1]Hugh W. McClellan, Subsurface distribution of pre-Mississippian rocks of Kansas and Oklahoma. Am. Assn. Petroleum Geol., Vol. 14, 1930, pp. 1535-1556.

[2]John S. Barwick, The Salina basin of north central Kansas. Am. Assn. Petroleum Geol., Vol. 12, 1928, pp. 177-199.

[3]H. S. McQueen, Insoluble residues as a guide in stratigraphic studies. Mo. Bur. Geol. and Mines. Appendix 1, 56th Bien. Rept.

[4]John S. Barwick, *op. cit.*

[5]F. C. Edson, Pre-Mississippian sediments in central Kansas. Am. Assn. Petroleum Geol., Vol. 13, 1929, pp. 441-458.

[6]Hugh W. McClellan, *op. cit.*

writer will use the Oklahoma terminology in this paper. The description of the insoluble residues of the Hunton and Viola limestones from the Schwalm well has been used as a basis of comparison for other wells in this area and is as follows:

Insoluble residues from the Hunton and Viola limestones in the Schwalm well, sec. 19, T. 12 S., R. 11 E., Kansas.

HUNTON LIMESTONE

Depth in feet	Description of Residue
2295-3000	Brown granular chert; small amount of white dolocastic[1] chert.
3000-3005, 3005-3010	Yellow and brown granular chert; bright marcasite; few rounded, frosted quartz sand grains.
3010-3020	Greenish gray shale, yellowish and brown granular chert.
3020-3025	White porous, in part dolocastic, chert; bright marcasite; greenish gray shale.
3025-3031	White porous, in part dolocastic chert; translucent chert.
3031-3037, 3037-3040	Rounded frosted quartz grains; white to yellow translucent chert.
3040-3045	White earthy to dense chert; little yellowish translucent chert.
3045-3053, 3053-3056	White earthy to dense chert; considerable angular to rounded frosted quartz grains.
3056-3062, 3062-3064	Angular to rounded frosted quartz grains; chert as above.
3064-3071, 3071-3083	Angular to rounded frosted quartz grains; abundant marcasite.
3083-3090	Soft green shale; round frosted quartz grains; white porous to dense chert.
3090-3096, 3096-3102, 3102-3106	Fine angular to rounded frosted quartz grains; white porous chert.
3106-3115, 3115-3119	Coarse angular quartz; bright marcasite.
3119-3125	Coarse angular quartz; green shale (dolocastic in part).
3125-3128, 3128-3137, 3137-3146	White earthy chert; white and yellow translucent chert.
3146-3155	Granular quartz and quartz sand; white chert.
3155-3165	Granular quartz and marcasite.
3165-3172	Granular quartz; soft gray shale.
3172-3179, 3179-3185	White earthy to dense chert; fine lacelike dolocastic chert.
3185-3188, 3188-3194	White earthy chert; fine lacelike dolocastic chert; black fissile shale.
3194-3204	Angular quartz; white chert; marcasite.
3204-3207	White earthy to dense chert; coarse oolites; coarse quartz grains.
3207-3210	Bluish chalcedonic oolitic chert; white chert porous to dense.

SYLVAN SHALE

3215-3280	

VIOLA LIMESTONE

3280-3285, 3285-3288	Gray fissile shale (from caving); quartzose material.
3288-3297, 3297-3300	Gray fissile shale; granular quartzose cavity fillings; white opaque chert.
3300-3315, 3315-3326	Brown granular or mottled chert; dolocastic brown chert; white to blue translucent chert.
3326-3328, 3328-3335	Brown granular and mottled chert; dolocastic brown chert; pale greenish dolocastic shale.

[1]Dolocasts are the casts or impressions of dolomite crystals preserved in the insoluble chert, shale, glauconite, pyrite and limonite. This term was proposed by H. S. McQueen, *op. cit.*

Depth in feet	Description of residues
3335-3340	Soft greenish and gray dolocastic shale; brown mottled chert.
3359-3364, 3364-3370, 3370-3383	Soft greenish and gray dolocastic shale; brown mottled chert; fine angular to coarse rounded sand grains.
3383-3389	Angular to coarse rounded quartz sand; brown mottled chert.
3396-3399	Dark brown mottled translucent chert; little quartz grains.

The Hunton limestone, as can be seen in the above description of insoluble residues, is characterized by a white finely dolocastic chert that is found in several zones of the formation. This chert is usually of delicate structure, the casts being tiny and the walls very thin giving the material a lace-like appearance. Another distinctive residue of the Hunton is the green to greenish gray shale which occurs as soft thin flakes that are very friable. This shale is generally without dolocasts, but a few fragments show small casts. In addition to these residues the Hunton contains a small amount of oölitic chert which has not been found in the Viola residues. This chert is usually bluish to bluish gray in color, resembling chalcedony in texture and the oölites are spherical in nearly all cases. Granular chert, both brown and white, and granular quartz are more abundant in the Hunton residues than in those of the Viola but are not confined to the Hunton.

The characteristic residues of the Viola limestone are the brown mottled chert and the brown and green dolocastic shale. The chert is abundant throughout the formation and ranges from light to very dark brown in color with a mottled appearance as a general rule. Some of the brownish chert shows fairly coarse dolocasts widely spaced, giving the chert a pitted rather than a porous appearance. The shales of the Viola residues are characteristically dolocastic, the casts being very small and closely spaced and giving the shale a porous appearance. The shales are brown, green, and gray in color, and are more compact than those found in the Hunton residues. Granular quartzose cavity fillings are also distinctive in the Viola residues and are usually clear and transparent.

The description of the insoluble residues obtained from Hunton and Viola limestones in the Jenkins and Scott Hayden No. 1 in sec. 8, T. 12 S., R. 14 E., Shawnee County, Kansas, is given so that a comparison can be made with the Schwalm residues.

Insoluble residues of the Hunton and Viola limestones in the Hayden well, sec. 8, T. 12 S., R. 14 E., Kansas.

HUNTON LIMESTONE

Depth in feet	Description of residues
2320	Soft flaky greenish gray shale; fine sand aggregates.
2340	Fine angular sand; granular white chert.

Depth in feet	Description of residues
2345	Soft flaky greenish gray shale; granular chert.
2350	Hard bluish and translucent chert; little pyrite.
2355	White granular chert; dense white chert.
2396-2401	Soft flaky greenish gray shale; coarse rounded frosted sand; white granular chert.
2401-2405	White dolocastic chert; dense gray chert; angular sand grains.
2405-2412	Coarse rounded frosted sand grains; white dolocastic chert.
2412-2417, 2417-2422	Soft flaky greenish gray shale; rounded frosted sand grains.
2422-2430, 2430-2445	Soft flaky greenish gray shale; white granular chert.
SYLVAN SHALE	
2445-2523	
VIOLA LIMESTONE	
2523-2530	Soft gray fissile shale; granular and quartzose chert.
2530-2538, 2538-2549, 2549-2560	Brown mottled chert; very finely dolocastic green shale.
2560-2565	Brown mottled chert; brown dolocastic shale.
2579-2586, 2586-2593	Gray fissile shale; finely dolocastic brown mottled chert.
2600-2605, 2605-2620	Brown mottled and white earthy chert (in part dolocastic); gray and green dolocastic shale.
2634-2640, 2640-2645	Green dolocastic shale; rounded frosted sand grains; gray chert.
2645-2655	Very dark brown chert; rounded frosted sand grains.
2655-2662	Coarse rounded frosted sand grains; gray dolocastic shale.

The use of insoluble residues as criteria for identification of beds has proven useful in connection with the Hunton and Viola limestones in the Forest City Basin. A few analyses of insoluble residues of the Hunton and Viola limestones in the Salina Basin have been made with results that suggest that the characteristic residues of the above beds persist wherever they are found in Kansas.

ALTERATION OF COMANCHEAN LIMESTONES OF SOUTH CENTRAL TEXAS

MARCUS A. HANNA[1]
Gulf Production Company, Houston, Texas

ABSTRACT

Evidence is presented to show that the recrystallized rocks of the Comanchean series vary from limestone to dolomites; that the faunal content has not governed the degree of dolomitization; that dolomites are distributed irregularly through the series; that unaltered limestones are present at various horizons; and that porosity is not a function of dolomitization or faunal content, but rather a function of recrystallization either with or without dolomitization.

Since the discovery of the Luling oil field,[2,3] Caldwell and Guadalupe counties in 1922, the Comanchean series of south central Texas has increased in importance because of the possibility that it may contain other prolific oil and gas fields. Since the discovery of Luling several other important fields have been found, the most important of which are Salt Flat[4] in Caldwell County, Darst Creek in Guadalupe County and Chittim in Maverick County. Several fields of lesser importance have been found in the Comanchean of this general area.

Because the first requirement for an oil reservoir is porosity, either primary or secondary as when superimposed through faulting, the subject of voids in the Comanchean series, together with the reason for their existence, has often been discussed by students considering this particular area. Porosity in this lime series was of importance to man long before the recent exploration for oil began. The presence of springs issuing through faults along the Balcones fault zone was the reason for

[1]Published with permission of the Gulf Production Company.

[2]W. E. Pratt, Oil at Luling, Caldwell County, Texas. Am. Assn. Petroleum Geol., Bull., Vol. 7, 1923, pp. 182-183.

[3]Ernest W. Brucks, Luling Oil Field, Caldwell and Guadalupe Counties, Texas. *In* Structure of Typical American Oil Fields (Am. Assn. Petroleum Geol.) Vol. 1, 1929, pp. 256-281.

[4]L. F. McCollum, C. J. Cunningham, and S. O. Burford, Salt Flat Oil Field, Caldwell County, Texas. Am. Assn. Petroleum Geol., Bull., Vol. 14, 1930, pp. 1379-1400.

the original location of several cities and towns of this area such as Austin, San Marcos, New Braunfels, etc. Previous to the coming of white men the springs and caves were used by the Indians.

The nature of the subsurface character of these limes previous to drilling, and especially prior to the use of the core-barrel, was necessarily conjectural. With advent of the core-barrel many excellent subsurface samples have been secured. The primary aim of those[1] responsible for the inception of the core-barrel was to secure samples from given depths to determine if the formations at these depths contained oil. With the successful securing of cores, need was soon felt for accurate formational correlations. Sedimentological[2] laboratories were established by many of the oil producing companies. The study of sedimentology, both organic and inorganic, received an impetus which has since carried it forward by leaps and bounds.

Cores from the Comanchean have been examined in several ways, depending on the type of material in each core. Washing methods are usually employed with shales and sands, such as the clays of the Del Rio, and the sands of the "Basement sands." The "Basement sands," however, are often partly or completely cemented with silica and other methods must be used. Samples of the less cemented and indurated materials are often examined in crushed samples, but for the most part this method is unsatisfactory in that the fossils, for instance, do not break free from the surrounding matrix. Thin-sections, polished sections, and chemical methods, including blowpipe analyses, have been found to be the most satisfactory.

Several years ago the writer read[3] a paper before the American Association of Petroleum Geologists in which he discussed some of the characteristics of the Edwards limestone. Since this paper was never submitted for publication a part of the information submitted at that time is incorporated in this paper. At the writer's request numerous chemical analyses have been made by the chemical department[4] of the Gulf Production Company. For this paper an attempt has been made

[1]In the Gulf Coast and south Texas area probably the first attempts to core were instigated by H. E. Minor of the Gulf Refining Company at Edgerley, Calcasieu Parish, Louisiana, in 1916. A scraping box on the side of the bit was first attempted.

[2]The word "sedimentology" and its derivatives, which are favored strongly by the author of this paper, are regarded by the Editor as undesirable, or at least dubious additions to scientific terminology because of etymologically hybrid derivation.

[3]Dallas, Texas, March 26, 1926.

[4]Analyses by E. T. Gregg and H. O. Nicholas.

to select from several thousand thin sections a few which most characteristically represent the alteration changes as found in the general lime section. The object of the present paper is to show something of this variation in alteration rather than to give thin-sections of the guide fossils found in the various members and zones of the Comanchean series. Many of the guide fossils are described or discussed in easily available publications.[1]

The Comanchean series of south central Texas is divided as follows:

Washita	Buda Del Rio Georgetown
Fredericksburg	Edwards Comanche Peak Walnut
Trinity	Glenrose Travis Peak Basement sands

In thickness the Comanchean series varies from a few hundred feet around the Central Mineral Region to more than 5,000 feet in Maverick County, Texas.

A subject which has received much consideration in geological literature is dolomite and dolomitization. The observations that have been presented are sufficient to warrant the conclusion that no one method of formation is sufficient to account for the occurrence of all dolomites. Dolomitization, either partial or complete, has taken place extensively in the Comanchean series particularly in the beds below the Georgetown. Nearly every paper describing the Comanchean rocks mentions dolomite but few indicate whether the whole series is dolomite, dolomitic, or whether the dolomites and dolomitic limestones alternate with limestones. Porosity is frequently mentioned with dolomite and dolomitic limestone, but it is not clear whether the porosity is due to dolomitization, and if so, how completely.

The Comanchean limestones and dolomites are almost wholly of organic origin rather than chemical precipitates. Some consist largely

[1]W. S. Adkins, Handbook of Texas Cretaceous Fossils, Univ. Texas Bull. 2838, 1928, pp. 1-303, pls. 1-37. Dorothy Ogden Carsey, Foraminifera of the Cretaceous of Central Texas, Univ. Texas, Bull. 2612, 1926, pp. 1-56, pls. 1-7. Merle C. Israelsky, Upper Cretaceous Ostracods of Arkansas, Ark. Geol. Surv., Bull. 2, 1929, pp. 1-20, pls. 1-4. Gayle Scott, Etudes stratigraphiques et paleontologiques sur les terrains cretaces du Texas, Thesis, University of Grenoble, 1926, pp. 1-215, pls. 1-3. H. C. Vanderpool, The Cretaceous Section of Maverick County, Texas, Jour. Pal., Vol. 4, 1930, pp. 252-58.

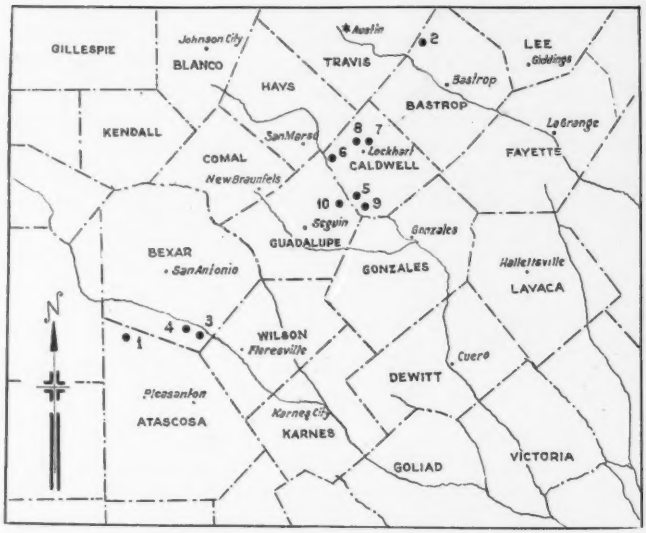


Figure 1. Map showing location of wells.

Atascosa County, (1) Ballard and Underwood No. 1 Hopkins; *Bastrop County*, (2) Knox No. 1 Lane; *Bexar County*, (3) Slick No. 1 Lamm; (4) Houston Oil Company No. 1 Mathney; *Caldwell County*, (5) Barrow No. 1 Grenshaw; (6) Foster and Rider No. 1 Brown; (7) Grayburg Oil Company No. 1 Blackwell; (8) Lockhart Oil and Gas Company No. 1 Schuneman; (9) United North and South No. 6 Rice; *Guadalupe County*, (10) United North and South No. 1 Englke.[1]

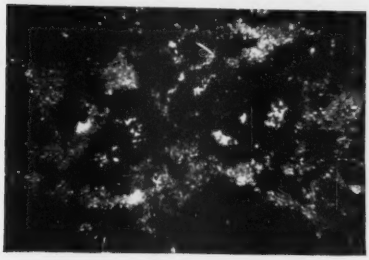
of foraminifera, while others are mostly composed of molluscan remains. The normal deposits are composed of the heterogeneous remains of almost all types of lime- and silica-secreting organisms which lived in Comanchean time. Variable percentages of argillaceous and arenaceous material

[1]Drawn by J. S. Woods.

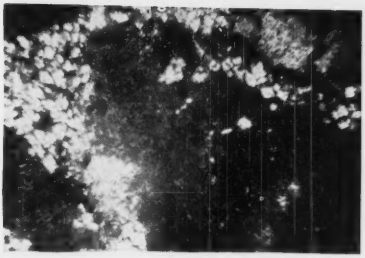
EXPLANATION OF PLATE 1

Well numbers refer to text figure 1.

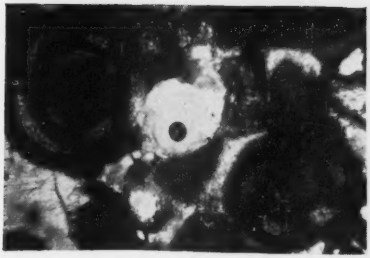
FIGS. 1.—Well 8, depth 1,685 feet, (45×).
2.—Well 7, depth 3,188 feet, (45×).
3.—Well 10, depth 2,474 feet, (45×).
4.—Well 7, depth 3,107 feet, (45×).
5.—Well 3, depth 2,910 feet, (26×).
6.—Well 4, depth 2,589 feet, (26×).
7.—Well 6, depth 2,483 feet, (45×).
8.—Well 1, depth 2,838 feet, (45×).



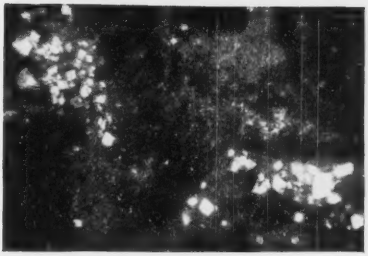
1



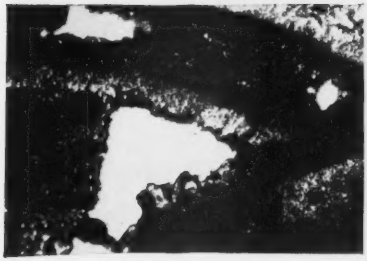
2



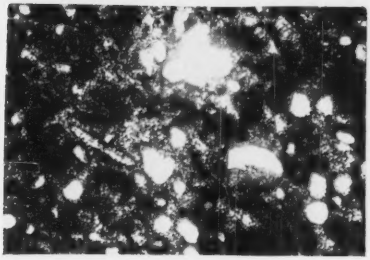
3



4

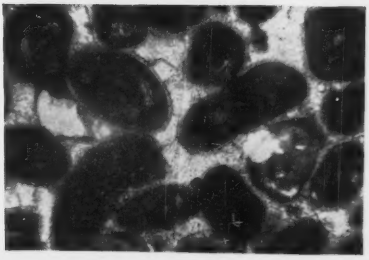


5



6

7



8

are present. The Del Rio formation is composed chiefly of clay, while the "Basement sands" consist of sand and shale.

A core from 2,474 feet in the United North and South No. 1 Englke in Guadalupe County is a very dense, light colored, finely granular lime in the hand specimen. In thin-section (pl. 1, fig. 3) the fine granulation is found to be due to the presence of abundant miliolid foraminifera which are imbedded in a clear calcite matrix. The core is almost non-porous. Such foraminiferal limes are not uncommon at various horizons in the Comanchean series. This particular one is from 108 feet below the top of the Edwards. In the Glenrose *Orbitolina texana* Roemer predominates in some zones rather than miliolid forms. This sample contained CaO 55.4 per cent, MgO 0.2 per cent and acid insoluble 3.2 per cent; the rock is therefore almost a non-magnesian limestone.[1] A core from 2,838 feet in the Ballard and Underwood No. 1 Hopkins in Atascosa County is similar to that from 2,474 feet in the Englke well, in the hand specimen. In thin-section (pl. 1, fig. 8; pl. 2, fig. 6) it is also similar. The core from 2,838 feet is from 560 feet below the top of the Edwards. It contains even less magnesium than the core mentioned above since the analysis shows CaO 55.0 per cent; MgO 0.1 per cent, and acid insoluble 0.74 per cent. These two cores show that at least some of the foraminiferal limes are quite pure and free from magnesium at the time of deposition.

A core from 3,107 feet in the Grayburg No. 1 Blackwell in Caldwell County in the hand specimen is mostly light gray but finely flecked with darker gray. There is a slight blotching of light shades of gray over the whole surface. The sample is from about the top of the Glenrose, and about 660 feet below the top of the Edwards. One of the sections (pl. 2, fig. 1) shows dolomitization of the groundmass and its encroachments into the shells. Two other sections of this core, mentioned later, show a smaller dolomite content than this one. Two analyses of this core show (1) CaO 44.8 per cent, MgO 2.53 per cent, acid insoluble 6.52 per cent; (2) CaO 46.48 per cent, MgO 7.6 per cent. They illustrate the local variation in per cent of magnesium in these rocks.

A second core from the Grayburg No. 1 Blackwell from 3,188 feet is similar in hand specimen to that from 3,107 feet. A section (pl. 3, fig. 8) shows the groundmass changed to dolomite, and the foraminifera partly replaced. Dolomite crystals appear in the center of the shell on the right hand side of the figure. Other sections from this core, mentioned later, show smaller and larger percentages of magnesium. Two

[1]Joseph P. Iddings, (Rock Minerals, 1911, p. 505) gives the following for dolomite, CaO 30.4 per cent, MgO 21.8 per cent.

analyses report (1) CaO 47.3 per cent, MgO 4.35 per cent, acid insoluble 4.8 per cent; (2) CaO 51.4 per cent, MgO 4.23 per cent. If parts of this core had been more carefully selected, considerably higher and possibly lower percentages of magnesium would have been found. These two sections are given to illustrate the partial alteration of a foraminiferal lime to dolomite.

A core from 2,483 feet in the Foster and Rider No. 1 Brown in Caldwell County (pl. 1, fig. 7) is a light to medium gray, slightly porous lime, in the hand specimen. It is from very near the top of the Edwards, since a core from 2,465 feet is in Georgetown. This core, containing numerous foraminifera, is very finely crystallized, but has not been dolomitized, since the chemical analysis shows CaO 54.2 per cent, MgO 0.3 per cent, acid insoluble 1.56 per cent. Two cores, mentioned later, from 2,495 and 2,498 feet, are dolomites. The section from 2,483 feet shows lime recrystallization without dolomitization as contrasted with dolomitization in the two sections from the Blackwell well.

A core from 2,589 feet in the Houston Oil Company No. 1 Mathney in Bexar County, in hand specimen, is a porous medium grayish brown to medium gray, finely crystalline limestone. It is from 125 feet below the top of the Edwards. The thin-section (pl. 1, fig. 6) shows complete recrystallization with many of the former fossils now represented by cavities. This is recrystallization and not dolomitization, since the analysis shows CaO 55.2 per cent and only a trace of magnesium.

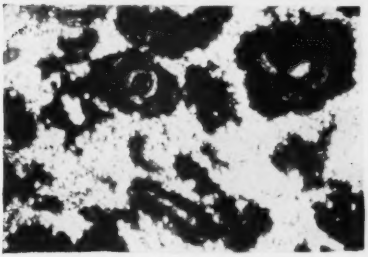
A core from 2,910 feet in the Slick No. 1 Lamm in Bexar County, in the hand specimen, is a very porous, molluscan lime, completely and fairly coarsely recrystallized. It came from 160 feet below the top of the Edwards. Something of the variation of the general character of this core is shown in thin-sections (pl. 1, fig. 5; pl. 2, fig. 7; pl. 3, fig. 7). The core is highly porous in part (pl. 1, fig. 5). The lime character of the core is well shown in the analysis, CaO 54.0 per cent, MgO 0.2 per cent and acid insoluble 0.84 per cent.

EXPLANATION OF PLATE 2

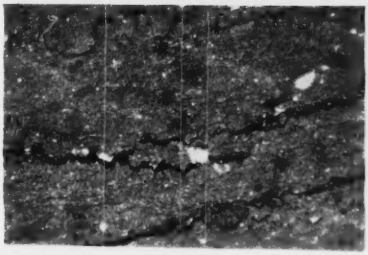
Well numbers refer to text figure 1.

FIGS.

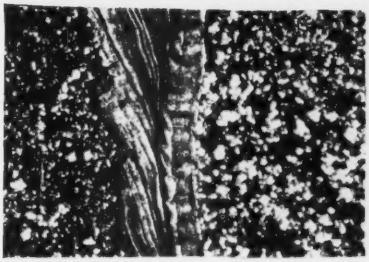
1.—Well 7, depth 3,107 feet, (26×).
2.—Well 2, depth 2,275 feet, (26×).
3.—Well 7, depth 3,188 feet, (26×).
4.—Well 7, depth 3,188 feet, (26×).
5.—Well 5, depth 2,264 feet, (26×).
6.—Well 1, depth 2,838 feet, (26×).
7.—Well 3, depth 2,910 feet, (26×).
8.—Well 6, depth 2,498 feet, (26×).



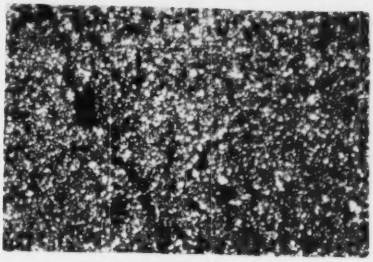
1



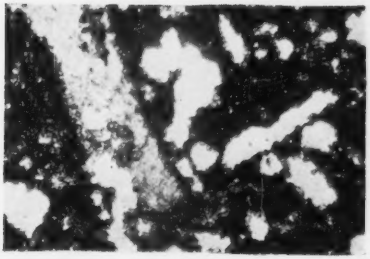
2



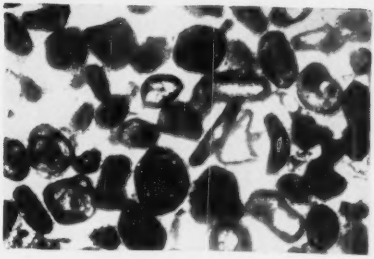
3



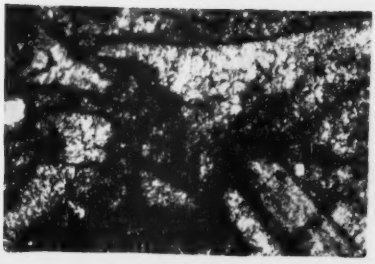
4



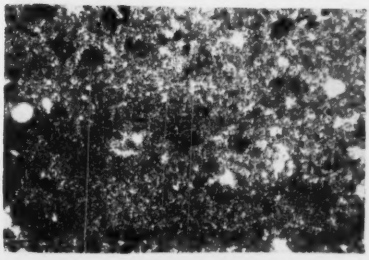
5



6



7



8

Recrystallization and dolomitization are virtually complete in the core from 3,188 feet in the Grayburg No. 1 Blackwell well (pl. 2, fig. 3; pl. 3, fig. 5). Only a few traces of mollusca remain. As stated above, parts of this core would have shown greater percentages of magnesium had a different selection of parts to be analyzed been made.

The core from 2,264 feet in the Barrow No. 1 Crenshaw in Caldwell County, in hand specimen, is a porous medium gray to grayish brown dolomite. In thin-section (pl. 2, fig. 5) it is seen to be a molluscan lime which has been completely dolomitized. The sample came from about 109 feet below the top of the Edwards. It contains CaO 33.3 per cent, and MgO 18.3 per cent.

Two cores mentioned above, from 2,495 and 2,498 feet in the Foster and Rider No. 1 Brown in Caldwell County, are grayish brown dolomites (pl. 2, fig. 8; pl. 3, figs. 1,4), although found only 12 and 15 feet respectively below the recrystallized lime at 2,483 feet already described. The analysis of the core from 2,495 feet shows CaO 31.8 per cent, MgO 19.5 per cent, and acid insoluble 0.9 per cent, while that from 2,498 feet records CaO 34.3 per cent, MgO 19.3 per cent, and acid insoluble 1.0 per cent.

A core from 2,085 feet in the United North and South No. 6 Rios in the Luling field, Caldwell County, is a dense, light to medium gray lime. It is from about 15 to 20 feet above the Edwards. The fauna of the Georgetown is heterogeneous as shown by thin-section (pl. 3, fig. 2). This core is a limestone containing CaO 52.8 per cent, MgO 0.3 per cent, and acid insoluble 4.4 per cent. Sections of a core from the Blackwell well at 3,188 and 3,107 feet respectively (pl. 3, figs. 3, 6) illustrate how a limestone carrying a heterogeneous fauna can be dolomitized. The lighter areas are dolomite. Analyses of these cores were given above.

A core from the Knox No. 1 Lane in Bastrop County from 2,275 feet is a very finely granular lime, characteristic of the so-called "adobe" limes. It came from only some 10 feet below the top of the Edwards. The "adobe" is a soft usually slightly brownish rock. This particular sample is limestone since it contains CaO 52.8 per cent and only a trace of MgO. Rolshausen[1] gives an analysis from the Humble No. 2 Johnson in the Salt Flat field, Caldwell County, from 2,666-2,677.5 feet showing $CaCO_3$ 83.3 per cent and $MgCO_3$ 11.1 per cent. Judging from these two analyses the "adobe" lime may be either a true limestone or a dolomitic limestone. The "adobe" may be, in a few instances, basal Georgetown, since traces of what appear to be Georgetown have been

[1]Am. Assn. Petroleum Geol., Bull., Vol. 14, 1930, p. 1409.

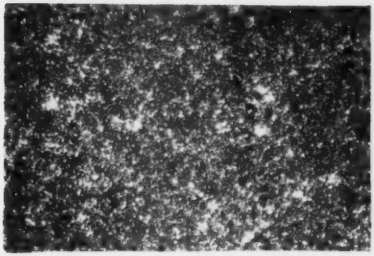
found in it. Certainty of these determinations, however, was not possible because of the recrystallized character of the material.

In summary, it can be stated that the limestones of the Comanchean series have not been governed in their alteration to dolomites by the character of the fossils they contain, since foraminiferal, molluscan, or varied faunal limes are found completely changed to dolomite, and also completely recrystallized without dolomitization. Dolomitization has not been confined to any particular formation. Porosity is not a function of dolomitization since some of the dolomites are highly porous, as are also some of the completely recrystallized limestones.

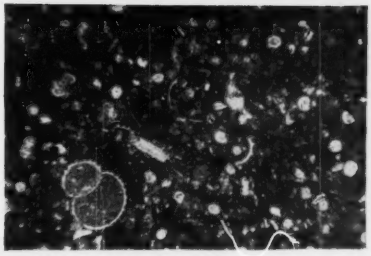
EXPLANATION OF PLATE 3

Well numbers refer to text figure 1.

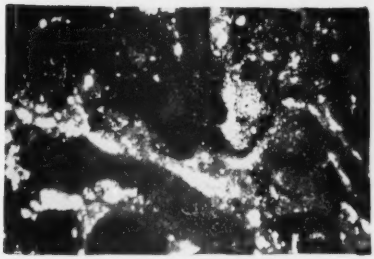
FIGS. 1.—Well 6, depth 2,495 feet, (26×).
2.—Well 9, depth 2,085 feet, (45×).
3.—Well 7, depth 3,188 feet, (26×).
4.—Well 6, depth 2,498 feet, (26×).
5.—Well 7, depth 3,188 feet, (26×).
6.—Well 7, depth 3,107 feet, (26×).
7.—Well 3, depth 2,910 feet, (26×).
8.—Well 7, depth 3,188 feet, (26×).



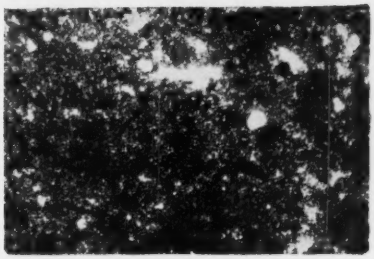
1



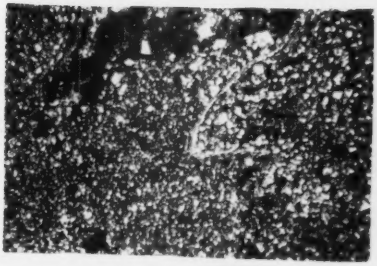
2



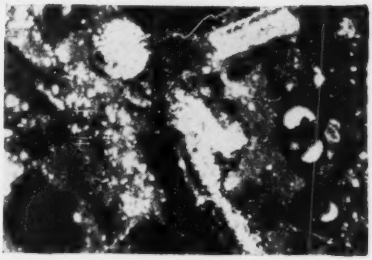
3



4

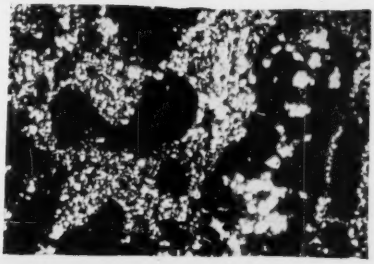


5



6

7



8

THE CLAY MINERALS AND THEIR IDENTITY

CLARENCE S. ROSS
United States Geological Survey, Washington, D. C.[1]

PAUL F. KERR
Columbia University, New York City

ABSTRACT

A study of the clay minerals is in progress and while not complete is yielding information about some of the fundamental minerals of sedimentary materials and the conditions that favor their formation. There are several kaolin minerals, but kaolinite is the only one that is likely to be found in sedimentary beds. Clays of the beidellite, montmorillonite, or other types are, however, more widespread in soils and shales than kaolinite. Calculations based on the assumption that kaolin is the typical clay-forming mineral are commonly in error.

The relationship between geologic processes and the formation of different types of clays is outlined; and also the way in which geologic conditions may be reflected by base exchange.

The minerals that characterize clays are one of the most widely distributed mineral groups and form the essential materials of some of the most continuous strata with which the sedimentary petrologist has to deal. Heretofore the determination of the clay minerals has offered so many difficulties that the members of this group have failed to yield their due quota of information about the mode of formation of shales, soils and clays. The first step leading to an interpretation of clay-bearing strata is an establishment of criteria that permit the recognition of the clay minerals which may occur in sedimentary deposits. The second is the determination of the genetic processes by which the different minerals may have formed.

Determinative mineralogy has undergone great advances within recent years, especially in the study of extremely fine-grained crystalline materials. The use of the petrographic microscope for the determination of indices of refraction in immersion oils has given us, for the first time a rigorous method of mineral identification. The comparison of the internal structures of fine-grained crystalline substances by means of their X-ray diffraction patterns has introduced an even more fundamental, though less convenient method of mineral identification.

[1]Published by permission of the Director, U. S. Geological Survey.

Correlation of the results obtained by these two methods with chemical analysis of materials of known purity gives us a research method capable of identifying any transparent crystalline material no matter how fine-grained. Truly non-crystalline materials are nearly if not quite absent among minerals. Most so-called amorphous minerals are in fact aggregates of sub-microscopically crystalline grains, and consequently there are few minerals to which the X-ray methods can not be applied.

For the past few years a study of the clay minerals has been carried forward in the laboratories of the United States Geological Survey, Columbia University, and the National Museum, with the support of the National Research Council. Much work remains to be done, but the results attained so far add materially to the fundamental knowledge of the clay minerals, and it is to be hoped will aid the petrologist in his interpretation of sedimentary materials.

It has commonly been assumed by many workers that kaolinite is the typical clay-forming mineral. This error has been suggested by various observers[1] but still persists. The recent work has shown definitely that kaolinite is one of the less important clay minerals of sediments, and that calculations based on the assumption of its presence are nearly always in error.

The clay minerals fall into several distinct groups. Up to the present four have been recognized—(1) the kaolin group; (2) the montmorillonite-bedellite group; (3) the potash-bearing clays and (4) a group occurring in many shales whose properties have not been definitely determined.

THE KAOLIN GROUP

A detailed study of the kaolin minerals is now in course of publication[2] by the United States Geological Survey, and only the essential properties need be outlined here. Kaolin has commonly been believed to be characterized by the single mineral kaolinite but this study has shown that there are at least three distinct kaolin minerals—kaolinite, dickite, and nacrite—each characterized by distinct optical, dehydration, and X-ray properties. Only the mineral *kaolinite* of these three is likely to be found in sedimentary materials and is of particular interest to the

[1]G. P. Merrill, What constitutes a clay, Am. Geologist, Vol. 30, p. 318, 1902. Heinrich Ries, Clays, p. 5, 1927.

[2]Clarence S. Ross and Paul F. Kerr, The kaolin minerals, U. S. Geol. Surv. Prof. Paper No. 165-E, 1931.

sedimentary petrologist. This is the mineral that makes up both residual and sedimentary kaolins. The properties of kaolinite are as follows: Color, white to light brown; habit, elongated crystals with a twisted worm-like form, varying in diameter from 0.001 to 3 millimeters; specific gravity about 2.6; cleavage, perfect on basal plane; approximate index of refraction about $\alpha = 1{,}560$, $\beta = 1.565$, $\gamma = 1.566$; birefringence, 0.006; optical character, negative; acute bisectrix, nearly perpendicular to cleavage plates; absorbs dyes readily and becomes strongly pleochroic. It should be noted that the optical properties that have heretofore been commonly ascribed to kaolinite have been found to belong to the distinct kaolin mineral for which the name dickite has been proposed. The most distinctive properties are the worm-like habit, the low birefringence, and nearly parallel extinction. The kaolin minerals as a group are readily distinguished by their low birefringence (0.006) from all other clay minerals whose birefringence is commonly 0.02 to 0.033. Thus even a casual examination of any clay-forming material will usually show the presence or absence of kaolinite.

Halloysite is a wide-spread kaolinite material that makes up part of many kaolin deposits and occurs locally as pure masses that appear to be amorphous. It is probably a finely divided material that differs from kaolinite principally in the state of division of the mineral particles. X-ray diffraction patterns indicate that halloysite is a sub-microscopically crystalline kaolinite. The dehydration curves are similar to those of kaolinite and the index of refraction is only slightly lower than the mean index of kaolinite, a result that would be expected from a slightly higher percentage of water.

Allophane is a clay material that has a resinous or hornlike texture and conchoidal fracture. The X-ray diffraction pattern indicates that allophane is the only truly amorphous mineral of the kaolin group. The patterns of allophane show only broad dispersion bands.

MONTMORILLONITE-BEIDELLITE GROUP

The montmorillonite-beidellite group is very complex and has not been fully studied, but it is perhaps worth while to outline the probable most significant properties. Minerals of this group are the characteristic clay constituents of many of the rocks with which the sedimentary petrologist has to deal. The first member, without name, has been found as an alteration product in some pegmatites. *Montmorillonite* is the clay mineral of most bentonites; *beidellite* occurs in some bentonite and many clays and shales; *saponite* is also probably at times an essential constit-

uent of bentonite. *Nontronite,* though not occurring in large deposits, is widely distributed.

The members of the group may be represented by the following approximate chemical composition:

$H_2O + H_2O$	$Al_2O_3 \cdot S2iO_2 + Aq$.....
$H_2O + H_2O$	$Al_2O_3 \cdot 3SiO_2 + Aq$ Beidellite
$H_2O + H_2O$	$Fe_2O_3 \cdot 3SiO_2 + Aq$ Nontronite
$H_2O + H_2O \cdot$ (MgO, CaO, etc.)	$Al_2O_3 \cdot 5SiO_2 + Aq$ Montmorillonite
$H_2O + H_2O$ $9MgO$	$Al_2O_3 \cdot 9SiO_2 + Aq$ Saponite

The first H_2O appears to be water of crystallization or "zeolitic" water; the second is high-temperature water of constitution; and the final Aq is extremely variable and loosely held adsorbed water. The total water is commonly 20 per cent or more in air-dried samples.

The members of this series seem to be completely isomorphous with one another although there is a tendency for a grouping of chemical analyses about individual members. The first member has the same composition as kaolinite, but the optical, X-ray, and dehydration properties are distinct from kaolinite, and are similar to those of other members of the group. Beidellite commonly contains ferric iron, and there are all variations between beidellite and nontronite. Bases, among which magnesium is commonly dominant, are not listed in the first three members of the group but all contain small but varying amounts of bases and are apparently isomorphous with a high magnesium end member probably represented by saponite.

The iron-free members are colorless, but with increasing iron content they assume a yellowish or brownish color and high iron beidellite and nontronite are greenish-yellow or epidote green. Some clays are pinkish commonly due to a small amount of manganese. In thin-section the clays of this group, as they occur in sedimentary beds, are commonly brownish, due to the presence of varying proportions of iron. The heating that a thin-section receives during impregnation with kolalith for hardening[1] seems to oxidize the iron and so materially deepen the color.

These clay minerals have a perfect micaceous cleavage and in thin-section may resemble small mica grains. In some shales the clay mineral forms perfect mica-like plates, but in others it has indistinct boundaries, or forms smear-like areas. The specific gravity is 2.0 to 2.1 and the hardness a little less than 2.5.

[1]Clarence S. Ross, Methods of preparation of sedimentary materials for study. Econ. Geol., Vol. 21, 1926, pp. 454-468.

The indices of refraction are much lower than for the kaolin minerals, being about 1.48 to 1.51 for the members low in iron, and increasing to a mean index of about 1.60 or higher for nontronite. The birefringence is about 0.03 for montmorillonite and beidellite and increases in the high end members. The optical character is negative, and the acute bisectrix nearly perpendicular to the plates. The colored varieties are slightly pleochroic.

POTASSIUM-BEARING CLAY MINERAL

A distinct clay material associated with certain ore deposits and the Ordovician meta-bentonites is characterized by essential potassium and a low-water content.

The potassium-bearing clays have not received adequate study and their chemical composition is not fully known. The following chemical formula approximately represents the composition of one that has been analyzed—$5H_2O_3 \cdot Al_2O_3 \cdot 5(MgO, CaO, K_2O) \cdot 15SiO_2$. They are low in water, high in bases of which K_2O forms an essential part, and all are high in silica.

The potassium-bearing clays are micaceous and resemble sericite; the hardness is about 2.5 and the specific gravity about 2.5. The color is light gray to pale yellow.

The index of refraction is about 1.53 to 1.565 and the birefringence is moderately high; ie. 0.02 to 0.03. The optical angle is very small and the optical character positive or negative. X-ray diffraction patterns show an abundance of lines which are different both in character and arrangement from those other clay mineral patterns.

OTHER CLAY MINERALS

The clay minerals listed above are those that are best known, but there are others. The most important of these occur in many shales and are similar to beidellite but give a more elaborate and distinctive X-ray pattern. Such patterns of a clearly related nature have been secured from late Tertiary claystone of the Pacific Coast, some types of Ohio shale and glacial varve clay of the Hudson Valley. Other clay minerals occur in gouge clays associated with mineral deposits, but probably do not concern the sedimentary petrologist.

The essential properties of the more important clay minerals are listed in the following table:

The foregoing table shows that some of the clay minerals have more distinctive optical properties than others. The low birefringence dis-

tinguishes the kaolin group from all others, and determinations within the group are probably not necessary in routine work since kaolinite seems to be the only member likely to occur in sedimentary beds. However, the inclined extinction and positive optical character of dickite is distinctive and crystal grains are easily distinguished from kaolinite. Nacrite is even rarer than dickite.

The optics of low iron beidellite and montmorillonite are the same and here the x-ray diffraction patterns are so far indistinguishable. For this reason only chemical analysis will determine which member is present. The presence of iron (i. e., the nontronite molecule) will be indicated by the brownish color in thin-section and by the higher index of refraction. The epidote green color and high index of refraction indicates nontronite. X-ray diffraction patterns also give different spacing from montmorillonite. The proportion of bases (i. e., the proportion of the saponite molecule) can probably be determined only by analysis, since the differences in spacing of the X-ray diffraction patterns are small.

The appearance of the potash-bearing clays is similar to that of the montmorillonite or beidellite in thin-section, but the higher index of refraction helps to distinguish this group. The chemical composition with a low-water and high potassium content and the X-ray diffraction pattern is distinctive.

The clay mineral optically similar to beidellite but with distinct X-ray properties has not been carefully studied, and its diagnostic characteristics are not known.

ORIGIN OF THE DIFFERENT CLAY MINERALS

Kaolinite. Kaolinite and halloysite are the result of the profound weathering of aluminous rocks, commonly granites and pegmatites. It has been assumed that feldspars invariably weather to kaolinite but this is not always true as they may alter to a beidellite-like clay mineral. The difference in the resulting clay mineral seems to depend largely on the conditions of weathering. Kaolinite is usually the result of very profound weathering processes; and commonly the conditions are analogous to those producing lateritization. It is also associated with bauxite and diaspore where even more profound leaching has removed most of the silica. Kaolinite may also form locally in beds underlying swamps where leaching by waters carrying humic acids, is effective; and associated with ore deposits where it is formed by the action of sulphuric acid developed by the oxidization of sulphides, on aluminous rocks. Kaolin

TABLE 1

Properties of the Important Clay Minerals

	Minerals	*Sp. G.*	*Indices of Refraction*			*Birefringence*	*Optical Character*	*Cleavage*	*Extinction*	*X-Ray Diffraction*
			α	*β*	*γ*					
Kaolin group	Kaolinite	2.59	1.561	1.565	1.566	.005		Perfect	Nearly parallel	Pattern distinct. Measurements on record
	Dickite	2.62	1.560	1.562	1.566	.006	+	"	V 15°-20	" "
	Nacrite	2.50	1.557	1.562	1.563	.006	−	"	V 10°-12	" "
	Halloysite			1.553		Isotropic		None		Similar to kaolinite but some lines suppressed
	Allophane					Isotropic				Broad dispersed bands
Montmorillonite-Beidellite group	Montmorillonite	2.0—2.1	1.492		1.513	.021	−	Perfect	Nearly parallel	All patterns similar, with small difference in spacing between opposite end members of group
	Beidellite	2.1—2.2	1.517		1.549	.032	−	"		
	Natronite	2.3—2.4	1.580		1.615	.035	+ or −	"		
	Potash-bearing clay	2.46	1.543		1.565	.022				Patterns distinct

beds are most widespread in the southern and southeastern parts of the United States where the weathering and oxidization is very deep. That is, in the residual materials of the southern Piedmont region and in the sedimentary beds of the Coastal Plain whose materials were probably derived from areas of deep weathering.

Montmorillonite-Beidellite group. Many marine shales; soils in the cooler and more moist portions of the country; and soils of arid regions where leaching is commonly not profound, are characterized by a clay mineral of the beidellite type, or another clay of closely similar appearance. Very commonly the presence of iron indicates isomorphism with nontronite. Pure nontronites are local in occurrence and probably do not form sedimentary beds.

The clay most commonly found in bentonites is montmorillonite, or a clay mineral belonging to the same series. The bentonite beds in the Upper Cretaceous of Arkansas, Oklahoma, and Texas, are of the beidellite type.

The clays of the montmorillonite-beidellite group seem to form in very different ways. The normal alteration of volcanic glass seems to produce a clay of this type. Not all volcanic glasses are unstable enough to alter to clay material and bentonites are most commonly derived from latitic glasses; that is, those high in feldspar, and containing little normative quartz. Ferro-magnesian minerals also seem to alter to beidellite or a related mineral more readily than do the feldspars. However, the latter may change to beidellite under some conditions. Thus in a granite gneiss at Washington, D. C., the feldspars can be observed altering directly to an iron-bearing clay mineral resembling beidellite. In the vicinity of the Comstock Lode, Nevada, considerable areas of andesite appear to have been altered to montmorillonite by the action of solfataric solutions. Montmorillonite also appears as a partial constituent of fullers earth from southern Georgia and Florida.

The beidellite type of clay minerals that are commonly formed in clays and shales have an alumina: silica ratio of 1 to 3 or higher, rather than the 1 to 2 ratio of kaolinite. Iron may be substituted for alumina and so form an essential part of the clay substance. In bluish or greenish clays the ferric iron is probably all present as clay material. In the lighter yellow clays it is probably largely present in the clay material, but a variable part may be present as hydrous iron oxides. In the deep red clays the iron is probably present largely as hematite. A deep red clay from Webb City, Missouri, formed by profound weathering of Missis-

[1]E. Posnjak, personal communication.

sippian limestone during the hiatus preceding the deposition of Pennsylvanian beds, proves by X-ray examination to be halloysite and hematite.

A few clay beds are known that contain clay minerals of both kaolinite and beidellite type. These seem to be formed by the partial kaolinization of clay beds that were deposited as beidellite, and also by the original deposition of a mixture of the two. In the latter case it is probable that the two types were derived from two distinct regions.

Under some conditions different minerals in a sedimentary deposit alter differently. A volcanic ash from Abatik River, northern Alaska, was originally made up of glassy material that has altered to montmorillonite and phenocrysts of biotite that have altered to kaolinite.

Potash-bearing clays. Clays of this type probably form a small proportion of many soils and possibly shales, but the only widespread beds of this type of material are the Ordovician meta-bentonites that have been recognized in Missouri, Minnesota, Wisconsin, Kentucky, Tennessee, Alabama, and eastward to Virginia, Pennsylvania, New York, and northward into Ontario. The conditions that favor the development of this type of clay are not known. A few clays are high in sodium, which suggests derivation from sodic rocks, or marine conditions of development but potassium is so much more readily fixed than sodium that deposition in sodium-rich water does not insure a sodic clay.

THE BASES IN CLAYS

The bases in clay vary in proportion and character as was pointed out in the discussion of the montmorillonite-beidellite group. Changes in the character of the bases reflect geologic differences under which they were deposited. Soil chemists have long been interested in the bases of clays, for these have a very important effect on the physical properties and fertility of soils, but the results of their investigation are of equal significance to the sedimentary petrologist.

In a large variety of clay materials magnesium is the dominant base, but calcium, potassium, and sodium are also important and a variety or other bases including ammonium may be present in small amounts. Under certain conditions bases of clays are exchangeable. That is, one base may be driven out and another take its place without any breakdown of the clay molecule as a whole. In some soils that have been profoundly leached under humid conditions so that decaying organic matter forms humic acids, a large part of the bases have been removed, and the hydrogen ion substituted in their stead. These acid clays correspond to an alumino-silicic acid while the normal base-carrying

clays are bases of such acids. In this way the gumbotils and the ball clays that commonly contain much carbonaceous matter are formed.

CONCLUSIONS

The foregoing discussion of the clay minerals, their properties and their mode of origin can only outline some of the ways in which a study of clays may aid the sedimentary petrologist in his correlations of beds and in an attempt to deduce the geologic conditions under which clay-bearing materials were formed. It is evident, however, that an understanding of clay materials is a potent aid to geologic research and the probability that we may gain other important geologic information from these minerals justifies their intensive study. The mineralogy of clay materials is not an important end in itself but it lays the foundation for genetic studies that will contribute greatly to geologic problems.

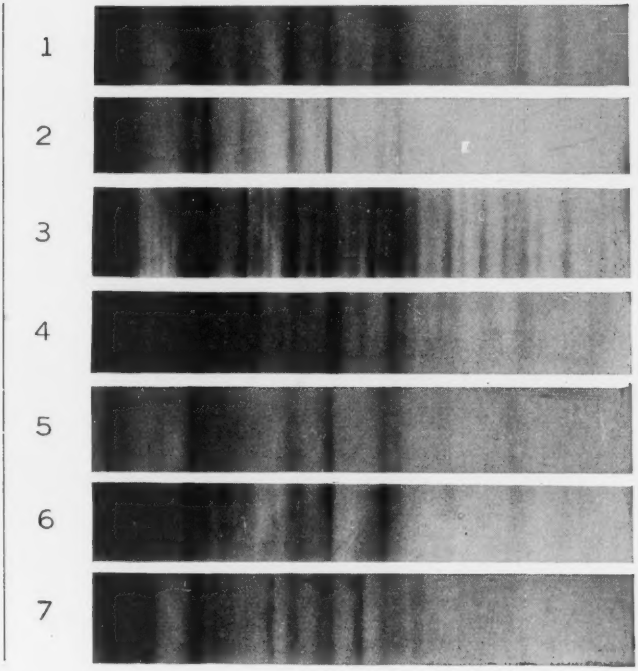


Figure 1. X-Ray patterns of the principal clay mineral types.

Nos. 1 and 2 are of the same type, and are representative of kaolinite, ($Al_2O_3 \cdot 2SiO_2 \cdot 2K_2O$); and anauxite, ($Al_2O_3 \cdot 3SiO_2 \cdot 2H_2O$).
No. 3 is a typical pattern of dickite, ($Al_2O_3 \cdot 2SiO_2 \cdot 2H_2O$).
No. 4 represents nacrite, ($Al_2O_3 \cdot 2SiO_2 \cdot 2H_2O$).
No. 5 indicates the montmorillonite-beidellite type of pattern, typical of bentonite.
No. 6 is illustrative of the potassium clay minerals.
No. 7 is a marine sedimentary clay from the top of the Pliocene strata in the Ventura basin, California.

EDITORIAL

SEDIMENTARY PETROLOGY IN RETROSPECT AND PROSPECT

HENRY B. MILNER
Imperial College of Science and Technology, London, England

The occasion of the first number of a journal devoted to the economic aspects of sedimentary petrology is indeed food for reflection. On the one hand we may look back on the chain of events which have made such a venture feasible; on the other, we contemplate the trend of the science and the part which such a journal is destined to play in influencing its evolution in the future.

In a commercial age, the territory of pure science is no longer inviolable. In whatever flights in theoretics we may indulge, sooner or later established fact, if it be capable of even only minor interpretation in practice, is acclaimed by industry and absorbed. The science thus becomes applied and from the academician springs the technologist.

Too seldom, perhaps, do we pause to acknowledge the obligation to its economic applications under which geology as a whole is laid. In whatever measure our subject has benefited industry, there has been a commensurate reward in the shape of new inspiration and experiment fostered thereby. Sedimentary petrology is undoubtedly a case in point. The principles on which this science rests, the methods involved in their extension and direction to many practical problems, now hold a permanent place in the field of public utility. Thus the science fulfils its mission and is itself exalted in the process.

That this state of things has not always been so, is soon made evident by a retrospect of the growth of the subject. Slightly more than twenty years ago studies in sedimentation and sediments as a whole were, with a few outstanding exceptions, conspicuously neglected, judged by present-day standards of technique and research. The lessons of Sorby and his successors were certainly not assimilated by geologists as a body, whose apathy to this branch of petrology in the period between his work and the end of the first decade of this century, was as well known as it was surprising. Such indifference dies hard even today with some of the more conservative members of the profession.

Then the vista suffered by vision through the wrong end of the telescope. The stratigrapher was content with a few general labels to describe his lithology. Sandstone was just sandstone and little more; when its color, texture and other superficial characters had been noted, it had been given its due, and nothing further commended it for study for its own sake, apart from that readily accorded to any indigenous fauna prevailing. The significance of such latent indices as accessory minerals, and especially of those quantitative elements which a thorough investigation of sediments could povide, was scarcely if at

all appreciated. And by contrast, rocks only incidental to the geologic column were studied with a degree of intensity which has never flagged and which has always been the outstanding feature of igneous petrology.

The innumerable instances in the annals of stratigraphy when faunas have been described without more than passing reference to the rocks in which they have lain entombed for geologic time, are remarkable. Indulgence in reconstruction of natural history entirely on organic evidence, without the slightest consideration for the story the sediment might itself unfold, is not uncommon today; it was quite conventional then.

In short, the general attitude toward sediments amounted to little more than lip-service to lithology, a subject with obvious limitations and monotonous to an extreme if nothing more than the hand-lens and powers of description be called upon. The application of microscopy, which made possible the science of igneous petrography, failed to awaken interest in deposits nearly always taken for granted until the "heavy" mineral asserted itself and proclaimed a new line of investigation.

However much we may seek to deplore and erase any impression of synonymity of "heavy" mineral work and sedimentary petrology, the fact remains that the pioneers in this field loosed the vitalising force which was destined to revolutionise events. At first the "heavy" mineral was regarded as an inconsequent accident, a fascinating departure from that knowledge which could be gleaned from thin-sections. Its precise bearings on the history of the deposit from which it was segregated remained for long unappreciated until at the end of the nineteenth century certain European investigators expounded its possibilities. Previously it had escaped attention, lost in the wilderness of undeciphered rock-matrix; the aggregate rather than the particle was scrutinized. Its advent substantially reversed the order of things. The particle became the goal of inquiry. Not only its composition but its size and shape were studied, thus individuality established. Detrital matter of all kinds was soon subjected to most minute analysis and the same principles were applied forthwith to consolidated rocks which, in a crushed state, became amenable to this treatment. Not only rocks of mechanical origin, but all types of sedimentary deposit were thus searched for the new evidence, with the result that this branch of petrology developed into a firm culture with a following destined in a short time to become international.

The science at its period of reanimation was fortunate in being able to draw upon a vast store-house of knowledge built up especially by the most learned mineralogists of the time. Much of the early enthusiasm centered in the fact that new adaptations of time-honored methods were rendered possible both in diagnosis and manipulation of sedimentary rock fragments. The quantitative element, hitherto lacking in this petrology, became an acknowledged desideratum; precision in measurement and expression compelled all the aid which crystallography and physics could afford. Sedimentary petrology thus came to embrace every relevant method of analysis capable of facilitating its study and gained enormously from the fact that its new terms of reference were widened by the appeal to so many sister sciences.

But with all these initial advantages, once the glamor of a new fashion had worn, the risk of stagnation was considerable. Analysis of whatever character and however exhaustively it may be conducted, loses much of its force

if it lacks interpretation, if its results fail to constitute new tenets of philosophy or at least to influence materially activities within the field with which it is concerned. Amassing data of mineralogical and mechanical properties of sediments might soon have palled but for two reasons: the significance of petrographic studies in stratigraphical research, particularly in problems of past physiographical environments, and the many and varied, albeit valuable, applications in every day commerce. The first alone would have proved quite sufficient to stabilise the science as a cognate branch of modern geology, but coupled with the demands of industry, accentuated both during and since the abnormal conditions of the Great War, its future importance was assured.

Wherever sediments are utilised to a practical purpose, sooner or later there arises some problem or other which trial and error methods fail to solve, where, in point of fact, data which only the petrologist can understand and interpret become essential. In many modern industries this has been proved over and over again. Let us take a few instances at random.

During the war, much expert petrological attention was devoted in Great Britain to finding raw material substitutes of equivalent or superior quality of rock previously obtained from foreign countries whose exports were either curtailed or prohibited entirely by the abnormal conditions prevalent. For example, the needs of the glass industry and the great ferrous and non-ferrous foundries had to be met, not only in the proving of adequate supplies of suitable material at hand, but what was a far greater proposition, in demonstrating unequivocally such suitability to conservative interests by appeal to scientific first principles. Where empiricism has reigned supreme for years, where certain materials have priority of use simply because they have always answered the purpose, not because of a knowledge that they possess any special technical merits, the problem of conversion is sometimes almost insuperable. In times of stress men are the more ready to lend a willing ear, and the war certainly did one great service in paving the way for closer understanding of essentials.

In a similar way intensive research into refractory materials for all kinds of high temperature work instigated inquiries into national resources of suitable siliceous rocks, actual and potential, in which the petrologist had to take an active part. In the ceramic and brick-making industries, apart from the resource question, people began to demand data of technical character concerning clays and allied rocks, a particularly difficult and at that time comparatively unexplored subject petrologically. The use of powders and finely divided material as adsorbents, for filtration and decolorising purposes, for asphalt products, paints and the like, for loading greases, and so on, brought about the inevitable interchange of chemical, physical and petrological knowledge, of lasting benefit to the industries concerned. And in this way the scope of petrological work was being constantly widened.

As an interesting sidelight on this trend of things, we may note the rôle of "heavy" mineral assemblages in questions of identification of sedimentary raw materials, both as regards geological horizon and possible locality. Two of the commonest problems raised in this connection are the checking of consignments of rock (crushed or otherwise) as conforming to specification, and analysis of competitive products when it is desired to ascertain what natural

raw materials may have been used in manufacture and why. Lithology itself is generally little positive guide; fossil evidence is probably entirely lacking; but "heavy" minerals abound in many things, in commodities as divergent in character as metal detergents, asphalte mastic, household sponges and ordinary dust. One has even heard of the possibility of the super-detective bringing a criminal to justice by appeal to petrographic methods in tracing the source of the mud on the miscreant's boots! But this seems altogether too dramatic.

The problem of identification of the source of origin of material which, on the face of it, would seem to carry not the slightest indication of its antecedents, is a very practical one where that material is natural rock. Its solution can only lie in competent knowledge of what we may term "stratigraphical petrology," also of its regional variations; and as this may frequently be lacking, the problem is not by any means always solvable. On the other hand, one can easily imagine the "heavy" mineral being the turning point in litigation where technical matters are involved, where the cross-examination of expert witness by learned counsel seeks to establish the plaintiff's case of substituted material against defendant's claim to honest adherence to specification: *sat sapienti.*

But of all the industries which, in recent years, have benefited from and have engendered research into sediments far and wide, that of exploitation of petroleum may perhaps be entitled to major credit. This is not merely a matter of "heavy" mineral identification and correlation of sands, the absurdly narrow view one hears often expressed. Subsurface geology is one of the most fascinating fields of investigation at all times. When its study involves possibilities of winning supplies of valuable commodities such as oil, it is rendered doubly absorbing by the accuracy of detail enforced thereby on the investigator. Every possible weapon of attack is launched in the attempt to elucidate underground stratigraphy, and petrology takes its place in the common armory of lithology and paleontology. And one of the immense advantages of this particular application of our subject is that, although it is in these circumstances pursued with an obvious economic motive, every scrap of the work involved is fundamental geology which gains slowly, but surely, in some place or other, from the continued effort to unravel its secrets.

It is opportune to utter a warning here. Unfortunately the welcome accorded the entry of petrographic methods in the field of petroleum geology was somewhat disproportionate to the regard for its limitations, which, once transgressed, might result in failures doing inestimable harm to a legitimate technique. The trying out of petrographic methods as potential to solving a stratigraphical problem which baffles other more precise lines of inquiry, is in itself always commendable, but it should be done without prejudice one way or another. Failure may be quite explicable to the geologist possessed of the facts, but to the layman caring only for results and value for money spent, it is little short of disastrous.

There are now on record many excellent examples of subsurface-, also of normal field-geology, in which petrological detail has figured prominently in the working out of stratal relationships, both in the realm of petroleum and

outside it. The archives of technical departments of many oil companies scattered throughout the world undoubtedly contain masses of such relevant information. But there are equally cases where petrographic methods have availed nothing, and in maintaining the correct perspective in this work we must never lose sight of that fact. It is all a question of sense of proportion and of foreseeing that this phase of sedimentary petrology does not suffer either from over- or under-estimation of its importance in any circumstances in which it may be invoked. Perhaps most vital of all is the care, incumbent on every worker in this field, that breadth of vision controls both the conception and execution of his task. The practical aspect may be in the foreground, but we must never forget that it is a geologist's duty to contribute constantly to his science, and that the real fascination and personal satisfaction of all these investigations lie in a realisation that that duty has been performed whenever possible.

By breadth of vision may be interpreted the desire to make every piece of research into sediments, whether petrological in the strict sense or whether concerned more particularly with processes and mechanisms, mean something real in the science as a whole. It may only be given to few to establish new and enlightening principles which deflect contemporary thought into untrodden channels, but it is the privilege of all to build solidly on those principles, to apply them in such a way that is progressive both in theory and in practice.

Thus we turn to the future. The question may be asked, what lies ahead of us in this subject? To what extent is sedimentary petrology capable of evolution as a science, what is its influence destined to be in geology as a whole?

It has been said, on more than one occasion, that sedimentary petrology is "played out," to use a colloquialism. This implies that all that will be, has been done: nothing remains but repetition. The peak of revival having been attained, nothing is in sight but an ultimate descent as long and as devoid of incident as possible. Were this indeed the case the outlook would be worse than hopeless pessimism, but fortunately there is no cause for such an indulgence.

A great deal depends on how we interpret the term "sedimentary petrology." If by this we mean simply the study of sedimentary rocks of all kinds, with and without the microscope, leading to mere systematic description (petrography), implying the use of standard methods and possibly the makeweight of guarded speculation, then the work ahead certainly does degenerate into a matter of routine, uninspiring, lifeless. But does it really mean this?

The fact of the matter is that the term itself is misleading as applied today. Few so-called sedimentary petrologists are content to stop short at the mere study and description of the rock, however detailed and precise they may be; their active interest extends to *everything* pertaining to sediments in whatever form the latter may appear. The word "sedimentationist" has been introduced to cover the vocation, but, besides being cacophonous, it implies one given to the study of sedimentation as a process, and hardly admits the product within its understanding.

Actually the student of sediments in geology has a multitude of varied interests and paths to knowledge from which to choose. He is concerned with

the genesis of material, both mother-substance and conception. The mechanism of growth of that material into the mass is as much his concern as that of the chemist and physicist similarly occupied. The environment in which the mass matures is equally his province. The subsequent changes it may undergo kindle his powers of observation and deduction. Its rendering into solid rock, processes of consolidation, metasomatism, destabilisation, disintegration and redistribution: all these, and many other factors, enter into the schedule of study of the modern student of sediments. These are mainly on the abstract side of his energies on the face of it, but actually concrete experiment contributes largely to these calculations. The more material petrology is thus surely only one part of a perhaps rather heterogeneous subject, but the latter none the less full of scope and opportunity for unlimited investigation.

To satisfy his craving for material on which to work out some chapter of natural history, this student of sediments obviously turns first of all to the rocks themselves. In this way description inevitably precedes genetical considerations. Possibly because there has been a superabundance of petrology and a less ostentatious display of petrogenesis in the realm of sediments, his activities hitherto have been misunderstood. Is it not a case of getting together all the evidence of the rocks, sifting it and then beginning the greater task of explanation? Are we not just now attaining the point when that explanation is commencing?

The moment we contemplate mechanism, for instance, we are faced with problems of sedimentation and precipitation, in themselves life-studies. In some cases our actual knowledge of the rock involved is so scanty *petrologically* that even to indulge in theory is risky. Take the case of many clay deposits; these frequently defy study by the ordinary methods; their microscopy is only practicable to a small percentage, and their constitution largely a matter of guess-work. So with mudstone, shale, and other aggregates of minute particles. This is in itself a field with vast possibilities for the courageous investigator and there is room for him in the company of many international colleagues at the present time.

In another direction the quantitative aspect of sedimentation and sediments has still much to be achieved. Classification is loose and unscientific. Nomenclature is to a large extent artificial, the product of custom and certainly unphilosophic, judged by other cognate sciences. Surely there is room for development and originality here?

Again, O. M. B. Bulman, in a contemporary article, draws attention to certain relationships between petrology as such and paleontology. Both branches of geology have undergone amazing evolution within latter years, but few attempts have been made to harmonize either their bearings or achievements. An appeal for coöperation is neither utopian nor is it a matter of ethics; it is an imperative aim which should underlie all work where the two sciences are jointly involved.

All this is in the realm of pure science. If we turn once again to economic applications then it is certain that the last word has by no means been said. New applications are inevitable with the progress of research and with the demands of technology. Empiricism, as we have before remarked, is still

in many activities awaiting supersedence by organised technical control and wherever sediments are exploited as raw materials there will always be room for the entry of new data and methods making for improvement in process and result.

It is clearly the function of this JOURNAL to foster research in the subject in every possible direction, to help the interpretation of academic thought that it may be adequately translated into practical politics, and above all to focus attention constantly on those problems wherein coöperation between petrologists and other scientists, both inside and outside geology, makes possible the furtherance of a common cause.